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PM_{10} SOURCE MEASUREMENT METHODOLOGY: FIELD STUDIES

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In measurement of PM-10 and total particulate matter, the precision of both the CSR and EGR techniques was found to be of the same magnitude as Method 17 (approximately 5%). A small bias was found between CSR and EGR PM-10 results (15%) and between EGR and Method 17 total particulate matter (10%). Although small, these observed differences, combined with the results of laboratory studies reported elsewhere, led to a recommendation for an increase in the length of sampling nozzles. This modification improved cyclone performance and is incorporated into the nozzle geometries described in the application guides for CSR and EGR.

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FOREWORD

Measurement and monitoring research efforts are designed to anticipate environmental problems, to support regulatory actions by developing an in-depth understanding of the nature and processes that impact health and the ecology, to provide innovative means of monitoring compliance with regulations, and to evaluate the effectiveness of health and environmental protection efforts through the monitoring of long-term trends. The Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, North Carolina, has responsibility for: assessment of environmental monitoring technology and systems for air, implementation of agency-wide quality assurance programs for air pollution measurement systems, and supplying technical support to other groups in the Agency including the Office of Air and Radiation, the Office of Toxic Substances, and the Office of Solid Waste.

The environmental effects of PM_{10} particulate matter are of concern to the Agency. Acceptable measurement methodology is critical for proper assessment of the impact on the environment of these emissions from stationary sources. Development and validation of measurement methods are key components for producing an acceptable method. Field studies were performed as part of an ongoing program for development and validation of methodology for the quantification of PM_{10} emissions from stationary sources.

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ABSTRACT

Two candidate measurement methods, Constant Sampling Rate (CSR) and Exhaust Gas Recycle (EGR), have been developed to measure emissions of in-stack PM_{10} particulate matter with aerodynamic diameter less than 10 μm. Two field tests were performed at the clinker cooler exhaust of a Portland cement plant to quantify precision and comparability of these techniques. In addition, accuracy was determined for total particulate measurement by comparison to Method 17. Collocated sampling trains were operated parallel with two Method 17 trains. In the second test, two CSR and one EGR train were operated parallel to two Method 17 trains. The operating procedures used for the CSR and EGR trains are described in detail.

In measurement of PM_{10} and total particulate matter, the precision of both the CSR and EGR techniques was found to be of the same magnitude as Method 17 (approximately 5%). A small bias was found between CSR and EGR PM_{10} results (15%) and between EGR and Method 17 total particulate matter (10%). Although small, these observed differences, combined with the results of laboratory studies reported elsewhere, led to a recommendation for an increase in the length of sampling nozzles. This modification improved cyclone performance and is incorporated into the nozzle geometries described in the application guides for CSR and EGR.

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SECTION 1

INTRODUCTION

In support of the ambient PM_{10} standard, the Quality Assurance Division of the Atmospheric Research and Exposure Assessment Laboratory at Research Triangle Park, NC (AREAL/RTP), has directed development and testing of two promising techniques for source in-stack PM_{10} measurements (Harris and Beddingfield, 1981; Farthing, 1983; Farthing et al., 1986; Williamson et al., 1984, 1985, 1988; Ward et al., 1985). This report summarizes test procedures and presents results of additional field tests at a Portland cement plant.

One of the PM_{10} techniques, the Constant Sampling Rate (CSR) approach, uses classical sampling hardware with an altered traversing protocol to restrict anisokinetic sampling bias to defined limits (Farthing, 1983; Farthing, et al., 1985). The other technique uses a new sampling train concept which incorporates exhaust gas recycle (EGR) to avoid sampling bias (Harris and Beddingfield, 1981; Williamson et al., 1984, 1985). Both sampling techniques use inertial size separation devices, such as a cyclone or a cascade impactor, to aerodynamically classify aerosol particles in situ, as described in more detail in Section 3. In some previous documents CSR was designated Simulated Method 5 (SIM-5) or Constant Flow Rate (CFR) and EGR was designated Emission Gas Recycle.

The EGR technique is designed to be comparable to Methods 5 or 17 for measurement of total particulate emissions, as well as determining PM_{10}. In general, the CSR technique is intended for PM_{10} measurements only, although it is appropriate in many circumstances for measurement of total particulate emissions.

Results of four previous field evaluations of these techniques indicated good agreement between EGR and CSR for PM_{10} and between EGR and Method 17 for total mass. However, a difference of 10% was indicated between EGR and Method 17 by one test using simultaneous, collocated runs. Differences of 10% between PM_{10} measurements of EGR and CSR were suggested by the results at two sites, but they were not consistent in sign of the differences from site to site. Previous tests did not measure precision of the techniques. As variations of the techniques are much smaller than source variations, simultaneous measurements by collocated sampling devices are needed to determine either precision or accuracy.

This new field work was performed in two tests at the same site. In the first, precision of the EGR technique was measured by comparing two

simultaneous and collocated trains, and accuracy for total particulate emissions was measured by comparison to two simultaneous and collocated Method 17 trains. Prior to this test, two upgraded EGR systems were built incorporating commercially available cyclones for the 10-μm (aerodynamic) size classifiers. The Method 17 measurements were provided by Entropy Environmentalists, Inc. (Research Triangle Park, NC). In the second test, precision of the CSR technique, comparability of the EGR and CSR techniques, and accuracy of both techniques for total particulate emissions were measured. In this test the same EGR and Method 17 trains of the first test and two CSR trains with commercially available cyclones were operated simultaneously and collocated.

Section 2 of this report gives conclusions and recommendations resulting from these tests. Section 3 summarizes the EGR and CSR techniques and describes recent alterations of hardware. Section 4 describes the site for the tests, and Section 5 describes the procedures which were used. The results and analyses are given in Section 6. Procedural details related to quality assurance (QA) are given in Section 7.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Sections 3 through 7 describe two field tests which evaluated precision and accuracy of the EGR and CSR techniques at the exhaust of the clinker cooler of a cement plant. This site was excellent for the purpose because the mass median diameter (MMD) of the aerosol was near 10 μm. Thus small variations in size separation were readily observable because much of the particulate mass was near the nominal size cut.

Precision in PM_{10}, PM_{10} fraction, and total mass concentration was good for both techniques. Combining between train and within train variations gave standard deviations of 2 to 4% and 4 to 5% for the EGR and CSR techniques, respectively. This compares to 4.7% observed in these tests for Method 17 in runs simultaneous with the PM_{10} probes. As expected, the precision of the EGR technique was better than the CSR technique.

The accuracy of the EGR and CSR techniques for total mass concentration, referenced to Method 17, was -10 ± 3.6 and -2 ± 4.4%, respectively. The cause of the bias in the EGR technique is not known but it suggests perturbation of flow into the nozzle by the cyclone size separator. The EGR nozzle extended 2.8 cm (1.1 in) in front of the cyclone with a 30° outside taper. The CSR nozzles extended 3.3 cm (1.3 in) in front of the cyclone with a 20° outside taper.

It appeared that one or both of the techniques tested biased PM_{10} concentrations, as indicated by the 16.2 ± 6.7% difference between the EGR and CSR results. From laboratory measurements of collection efficiency versus particle size (Williamson et al., 1988) the most likely cause was a decrease in the cut diameter of the cyclone associated with the geometry of the EGR nozzle. At the duct velocity of these field tests the decrease in size cut was 29%, whereas a decrease of 40% was observed at higher nozzle velocities. Increasing the distance from the EGR nozzle inlet to the cyclone inlet eliminated this effect on the cyclone behavior.

It is recommended that evaluation of precision and accuracy in field tests similar to those described herein be continued. Nozzles extended in length to eliminate sampling bias and the effect on cyclone behavior should be utilized. Performance of these techniques at several types of sources such as cyclic processes and wet particulate streams, is not known and should be tested. It is also recommended that nozzles for cascade impactors be evaluated and improved, because the effect of nozzles on cyclone behavior relates directly to inertial impaction caused by high-velocity jets.

SECTION 3

CANDIDATE PM_{10} TECHNIQUES AND EQUIPMENT

The technical difficulties in size-specific (i.e., PM_{10}) particulate sampling are greater than, but similar to, those of total particulate sampling by EPA Reference Methods 5 or 17. Potential sampling biases exist because of variations in the spatial distribution of particulate concentrations across the sampling plane defined by the duct cross section. Likewise, temporal variations in particulate concentrations due to process variations can cause inaccurate or unrepresentative emissions measurements. EPA Reference Methods for particulate sampling (Methods 5 and 17) deal with these problems by specifying the sampling location to minimize stratification (Method 1). Spatial and temporal averaging is achieved by using a traversing protocol which collects a velocity-weighted average of the particulate emissions at an array of points spanning the sample plane. Specifications also require at least three separate measurements, providing further temporal averaging. A second potential error in particulate measurements is duct/nozzle sampling bias. Unless the gas velocity, u, entering the sampling nozzle equals the local duct velocity, v, particulate matter will be selectively depleted or enriched in the sample gas stream because of inertial separation at the nozzle entrance. The effect of anisokinetic sampling has been characterized by Belyaev and Levin (1974) in terms of an aspiration coefficient, A, defined as measured concentration/actual concentration:

$$A = 1 + (R-1)\frac{B}{B+1} \qquad (3\text{-}1)$$

where R = velocity ratio v/u,
$B = (2 + 0.617/R)K$,
K = particle Stokes number with respect to the nozzle, $\tau v/d$,
τ = particle relaxation time, $CD^2/18\mu$ (s),
C = Cunningham slip factor,
D = particle aerodynamic diameter (cm),
μ = gas viscosity (poise), and
d = nozzle diameter (cm).

Note that B is proportional to particle diameter squared so anisokinetic sampling bias becomes more pronounced as particle diameter increases. For total particulate sampling (such as Methods 5 and 17), this bias is restricted by specifying isokinetic sampling (within a 10% tolerance) at each point. This tolerance is easily attained in sampling which is not size specific by varying the sample flow rate so that nozzle velocity is within 10% of stream velocity.

The potential problems described above are enhanced in PM_{10} sampling because inertial size segregation must be performed. Any inaccuracies in the inertial cutoff diameter, which is determined by sample flow rate, will lead to errors in the PM_{10} measurement by misclassification of particulate matter in the size range near 10 µm. Misclassification of particles larger than 10 µm can also occur because of bounce or reentrainment, causing these particles to be counted in the PM_{10} fraction. Likewise, if extensive deposition of particles smaller than 10 µm occurs upstream of the inertial sizing device, then the PM_{10} fraction will be depleted, even if the nozzle deposits are reentrained as agglomerates and pass into the sizing stage. All these potential problems must be faced in a PM_{10} sampling strategy.

The most obvious potential inaccuracy in PM_{10} sampling is due to a built- in anisokinetic sampling bias. Inertial sizing devices (impactors and cyclones) are available which have a sufficiently sharp collection efficiency at 10 µm, but only for specified flow rates which are dependent on gas temperature and composition. This fixed flow rate requirement precludes isokinetic sampling in the manner of Method 5 with existing sampling trains. Because anisokinetic sampling bias can be significant for particles near 10 µm, this effect cannot be ignored.

Previous work on this problem by EPA and at Southern Research Institute (SRI) has led to the development of two potential sampling methods, the EGR sampling train and the CSR traversing protocol. The EGR train in principle eliminates the problem of anisokinetic sampling bias by simultaneously allowing isokinetic sampling at the nozzle and fixed-flow operation at the inertial sizing device(s). The train design allows the isokinetic flow of gas into the sampling nozzle to be augmented by an adjustable amount of filtered, recycled stack gas upstream of the inertial sizing device. The CSR protocol is an alternate candidate PM_{10} method, which uses existing sampling equipment (cyclones or cascade impactors without special gas recycle adaptations). This protocol involves synthesizing a duct traverse with fixed-flow-rate runs by using different sampling nozzles if necessary so that the nozzle velocity at each sample point does not fall outside a specified range relative to the isokinetic velocity at that point. Both techniques are described further in the remainder of this section.

EXHAUST GAS RECYCLE TECHNIQUE

The principle of operation of the EGR train is illustrated in Figure 3-1. Stack gas is extracted isokinetically at volumetric flow rate Q_s. If the stack moisture fraction is B_{ws}, the sample flow consists of $Q_s \cdot B_{ws}$ moisture and $Q_s(1 - B_{ws})$ dry gas flow. At the mixing point a flow, Q_r, of dry recycle gas is added to the sample stream to bring the total flow rate to the predetermined constant level, Q_t. In the impingers or condenser, the moisture content of the sample gas, $Q_s \cdot B_{ws}$, is removed. After the pump and total flow metering element, the recycle flow Q_r is diverted by means of an adjustable valve. By mass balance, in a leak-free system the remaining flow which passes the dry gas meter and orifice will simply be $Q_s(1 - B_{ws})$, exactly as would occur in an isokinetic sampling train without gas recycle.

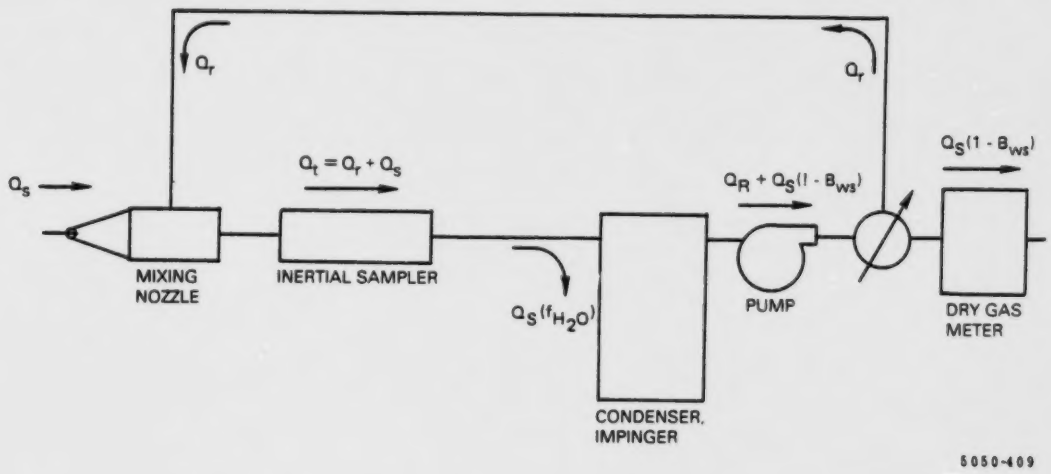


Figure 3-1. Gas flow in exhaust gas recycle train (Harris and Beddingfield, 1981).

There are several practical requirements for a functional EGR sampling system. The operator must accurately monitor and control two flow rates rather than one. Setup and operation of the train must be simple, and the train must function reliably in normal field sampling environments. The recycle gas mixing must not cause extraneous particle deposition, the recycle rate must not affect the cutpoint of the inertial sizing device, and artifact particulate matter must not be introduced.

A block diagram of the EGR train is shown in Figure 3-2. Stack gas is isokinetically extracted through the sample portion of the EGR mixing nozzle into the inertial size separator of the sample train. After passing the inertial sizing device(s) and in-stack sample filter, the sample gas passes through the probe and condenser or impinger train and into the EGR flow control module. As in conventional Method 5 control modules, the gas flow rate entering the control module is controlled by coarse and fine control valves (V_1 and V_2, respectively) at the entrance of the sealed pump. At the exit of the pump and absolute filter, the total flow is measured with a laminar flow element (LFE; Meriam model 50MJ10-1/2, type 10). The gas stream is then split into the recycle and sample flow lines. The sample flow is monitored in the normal manner by a dry gas meter and a calibrated orifice. The recycle gas flow rate is measured with a second LFE (Meriam model 50MJ10-1/2, Type 11). The partitioning between sample and recycle gas is controlled by valves V_3 and V_4 located downstream of the LFE. Valve V_5 was added to the system to extend the range of control to higher recycle percentages by adding back pressure to the sample flow line. The recycle gas line, along with the sample and pitot lines, passes through the heated probe, in which the recirculated gas is reheated to the duct temperature. Power to the heater is regulated by a proportional temperature controller by using a thermocouple reference sensor located on the surface of the recycle tube.

Operation of the EGR train is similar to standard Method 5 sampling. The total dry gas flow $Q_r + Q_s(1 - B_{ws})$ is monitored by using the total flow LFE and controlled by using valves V_1 and V_2. The sampling flow Q_s (defined as the gas flow rate entering the nozzle) is monitored by using the sample orifice and dry gas meter in the normal manner of Method 5 sampling, and it is controlled by using the recycle valves (V_3 and V_4) and the back pressure valve (V_5). Selection of traverse points and sample flow rate are done by standard techniques. In practice, the total flow would first be set to its operating value for the desired size cut(s), then the sample flow rate adjusted to be isokinetic at the first traverse point. Changes in the recycle flow setting alter the total flow only slightly, so that usually one or two iterations of V_3 and V_4 are needed at a new traverse point. V_5 needs to be adjusted only when the maximum recycle flows needs to be attained. The only aspect that can be initially confusing to a trained Method 5 operator is that the sample flow rate is adjusted with the recycle valves rather than the customary valves V_1 and V_2.

A more complete description of the EGR technique may be found in Martin et al. (1988).

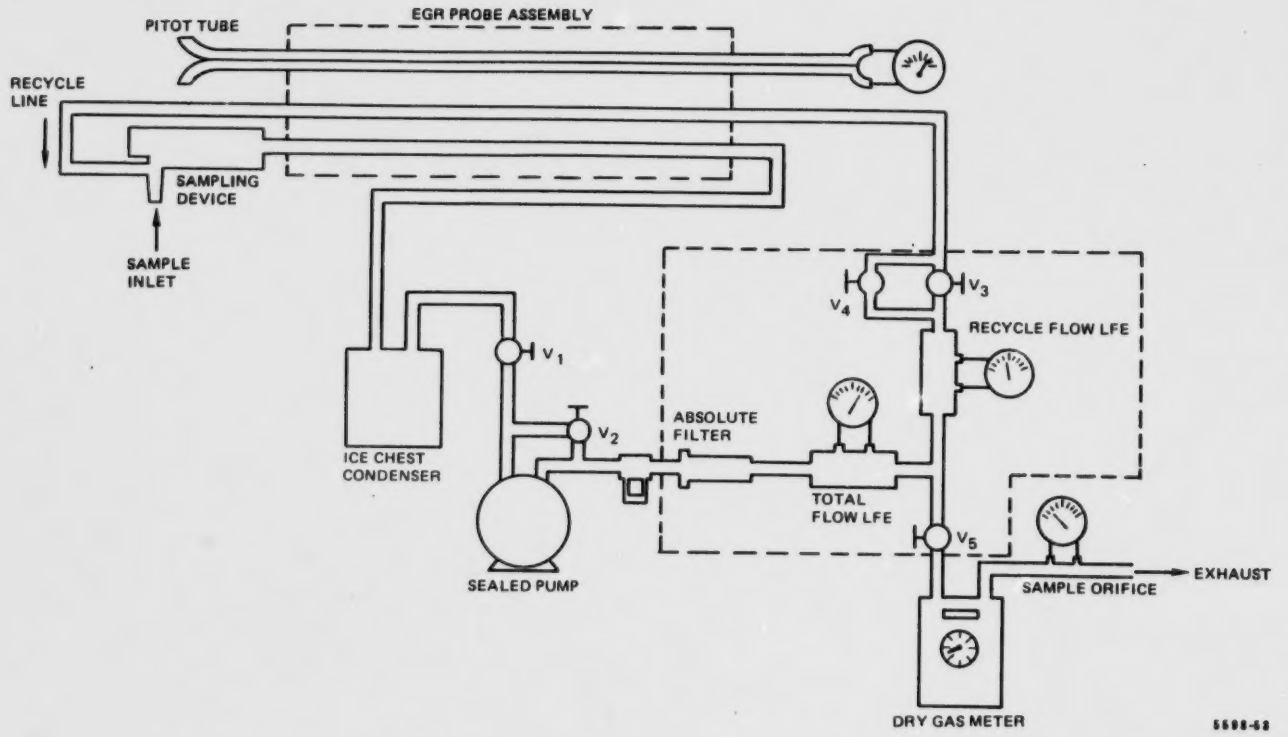


Figure 3-2. Schematic of the exhaust gas recycle train (Williamson et al., 1984).

CSR TECHNIQUE

The EGR train offers the potential to allow routine PM_{10} sampling without greatly exceeding the accuracy, cost, and complexity expected for Method 5 sampling. At present, however, EGR sampling equipment is still in developmental stages and is not commercially available. It is not certain if or when this technique will be commercialized, and if it will be suitable for all emission gas streams of interest. The CSR technique was developed to allow immediate PM_{10} sampling with commercially available equipment.

As discussed in the introductory paragraphs, potential errors in PM_{10} sampling arise from several sources. First, spatial variation of particulate concentrations across the duct will cause sampling error. The magnitude of this error is generally reduced by increasing the number of sampling points traversed. Other sources of errir, such as temporal variations in the emissions and random measurement uncertainties, likewise may be reduced by increasing the number of samples. Finally, errors due to anisokinetic sampling depend on several factors which can be only partially controlled, such as the magnitude and variation of the stream velocity over the traverse grid, the required sample flow rate, and the particle size distribution. These errors were analyzed in detail in the final report to the CSR development task of EPA Contract 68-02-3118 (Farthing, 1983).

Several potential PM_{10} sampling protocols can be imagined which use existing inertial sizing equipment. In theory, an inertial sizing train can be run by using a full Method 5 isokinetic traverse. This option is unrealistic for PM_{10} because changes of nozzles for each small ($\approx$10%) variation in duct velocity would be necessary to satisfy the criteria of isokinetic sampling and specified gas flow rate required by the inertial size separator to define the PM_{10} size cut. A second option is to sample a representative traverse grid (chosen by Method 1 or other criteria) at a constant flow rate determined by the inertial sizing device. This option is the one usually chosen for particle size distribution measurements. Typically, when this option is chosen, enough traverse points are used so that the dominant error source is expected to be anisokinetic sampling bias. At the other extreme, the operator may choose to minimize isokinetic sampling bias by operating the PM_{10} sampler at near-isokinetic conditions at a single point. In this case, errors due to spatial variation are expected to dominate unless a traverse is synthesized by multiple single-point samples at different duct positions. The sampling option expected to have greatest accuracy is a synthesis of several single-point, near-isokinetic runs into a traverse. This option unfortunately is the most expensive in terms of on-site sampling time. Other sampling protocols may be suggested. For example, one approach which has been used involves replicate single-point cascade impactor sampling to obtain a measure of the PM_{10} fraction of the particulate emissions. This fraction is applied to the total mass concentrations (as determined by Method 5) to obtain a value for the PM_{10} concentration.

All of the protocols generally outlined above involve compromises between cost and total measurement uncertainty. For different choices of sampling strategy, the measurement uncertainty may be dominated by spatial or temporal variation of particulate emissions, by anisokinetic sampling bias, or by inherent errors of measurement. Typically, sampling strategies for specific sites are developed without a clear, quantitative picture of the magnitude and dominant source of the measurement inaccuracy to be expected.

In developing a candidate CSR strategy (Farthing, 1983), an approach was selected which allows expected measurement errors to be contained within predetermined limits. The objective of the protocol is to minimize total costs while reducing errors due to anisokinetic sampling and spatial variation to less than that expected from temporal variation of emissions. Anisokinetic sampling bias is limited by synthesizing a full duct traverse from partial traverses, if necessary, by using nozzles of different diameters to keep the velocity ratio R (of Equation 3-1) within acceptable limits. Points for each partial traverse (i.e., each nozzle size) are selected which have duct velocities in the range which prohibit error due to anisokinetic sampling of 10-μm particles (aerodynamic) from exceeding ±20% at any point. Actual errors can be expected to be much less, because anisokinetic sampling error decreases with the inverse of size to the second power and PM_{10} includes all particles with aerodynamic diameters less than 10 μm. Furthermore, aerosols encountered in process streams have substantial mass fractions at sizes well less than 10 μm. For most sources, the limits defined above keep error due to anisokinetic sampling to less than ±11% (Farthing et al., 1985). In most instances, one nozzle is sufficient for the entire traverse.

From a general view, CSR formally imposes limits, as stated above, upon the velocity ratio R of Eqn. (3-1) such that error due to anisokinetic sampling of 10 μm particles is less than ±20%. These limits, R_{min} and R_{max}, are presented in Figure 3-3 as a function of stream velocity for various assumed values of $\mu Q^{1/2}$, where Q is the actual flow rate (acfm) through the nozzle and μ is the viscosity in micropoise. An important feature of these limits is that they diverge as duct velocity decreases. This means that the criterion for matching nozzle velocity to duct velocity relaxes at lower duct velocities without increasing sampling error. At $\mu Q^{1/2}$ values typical of combustion streams and commercial samplers (750-1310), the range encompassed by R_{min} and R_{max} is substantially larger at most encountered duct velocities than the minimum of ±20% which occurs at very high duct velocities.

The limits presented in Figure 3-3 originate from Eqn. 3-1; aerodynamic particle diameter (D) is set at 10 μm, and aspiration coefficient (A) is set at 0.8 for R_{min} and 1.2 for R_{max}. With the additional substitutions for nozzle diameter, $d = (4QR'/v\pi)^{1/2}$, and solving for stream velocity, Eqn. 3-1 becomes

$$v^{3/2} = \frac{36\ (A - 1)\mu Q^{1/2}\,(R')^{3/2}}{\pi^{1/2}\,(R' - A)\,(2R' + 0.617)\,(10\mu m)^2} \qquad (3\text{-}2)$$

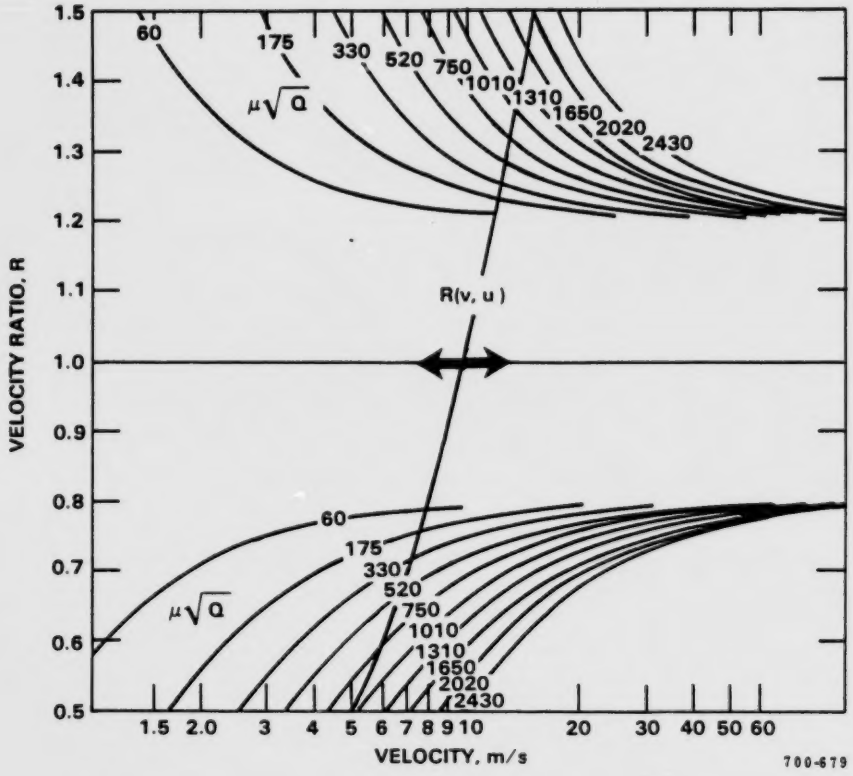


Figure 3-3. Velocity ratios R_{min} and R_{max} versus duct velocity giving aspiration coefficient of 0.8 (lower curves) and 1.2 (upper curves) for 10-μm particles (Farthing et al., 1985). R (v, u) is the function R = v/u for constant u, used in specific application of CSR.

where R' represents R_{min} (when A = 0.8) or R_{max} (when A = 1.2). The appropriate value of $\mu Q^{1/2}$ depends upon the sampler, the gas temperature, and the composition of the gas. If a single-stage PM_{10} sampler is used, Q should be the flow rate which provides a 10 µm size cut. With a cascade impactor, the flow rate is somewhat adjustable but should be selected to produce at least one size cut above or very near 10 µm.

The effect of the Cunningham slip factor (C) is ignored because including it would unnecessarily complicate the procedure. Its effect is very small at high duct velocities and is limited to a few percent (≈2%) at low duct velocities, where |A-1| can be expected to be smaller.

In practical application of CSR for a given source, it is necessary to determine the range of duct velocities which are acceptable for each of several given nozzle sizes. This can be performed with Figure 3-3 or by direct calculation. The curve designated R(v,u), running in a nearly vertical line, is used to read the appropriate ratio limits, R_{min} and R_{max}, from the figure. The corresponding limits of duct velocity which can be sampled with a given nozzle are then given by $v_{min} \equiv uR_{min}$ and $v_{max} \equiv uR_{max}$, where u is a constant corresponding to the PM_{10} flow rate for a particular source and a given nozzle size. The curve R(v,u) is the function $R \equiv v/u$, with u constant, and has the same shape (or slope) no matter where it is centered on the "R=1" or "v=u" axis. It is shifted left or right so that its center (at R=1) matches the nozzle velocity u. The limits, R_{min} and R_{max}, are the values at which the vertical curve intersects the limit curves appropriate for the $\mu Q^{1/2}$ value for the source.

The limits depicted in Figure 3-3 are broad enough that the velocities in a point-by-point traverse at most sources will fall within the specified limits. However, in some ducts, velocities at some traverse points will be outside of these limits for one nozzle. In that circumstance, additional nozzles, having limits which include the other velocities, should be used, and the traverse should be divided into two or more subtraverses with different nozzle diameters. At this time it is left to the judgment of the operator whether to change the nozzle during the run or to perform each subtraverse as a separate run. The associated problems vary with the circumstances. Particulate material caught in the nozzle does not count for PM_{10}. However, if one wishes to use the run as a measurement of total particulate, as well as PM_{10}, then the nozzle catch is important. Further data are needed from tests in actual sampling conditions in which the nozzle is changed on some runs and not in others.

The frequency of tests in which one nozzle size is not sufficient for the complete traverse is related to the increments of nozzle sizes available. Performance of a velocity traverse before the sampling run permits selection of the optimum nozzle size available. Small increments for the nozzle sizes increase the likelihood that a nozzle size will be available to

give a nozzle velocity midway between the range of stream velocities. The likelihood is then less that stream velocities will exceed the limits for the chosen nozzle, and sampling error is lower. Thus, using smaller nozzle increments simplifies the measurements, and improves the accuracy. A ratio of adjacent nozzle sizes of 1.1 gives a ratio of nozzle velocities of 1.21. Ten of these nozzles are required to provide nozzle velocities ranging from 18 to 100 ft/s. By the CSR protocol these nozzle velocities accommodate stream velocities ranging from 10 to 120 ft/s.

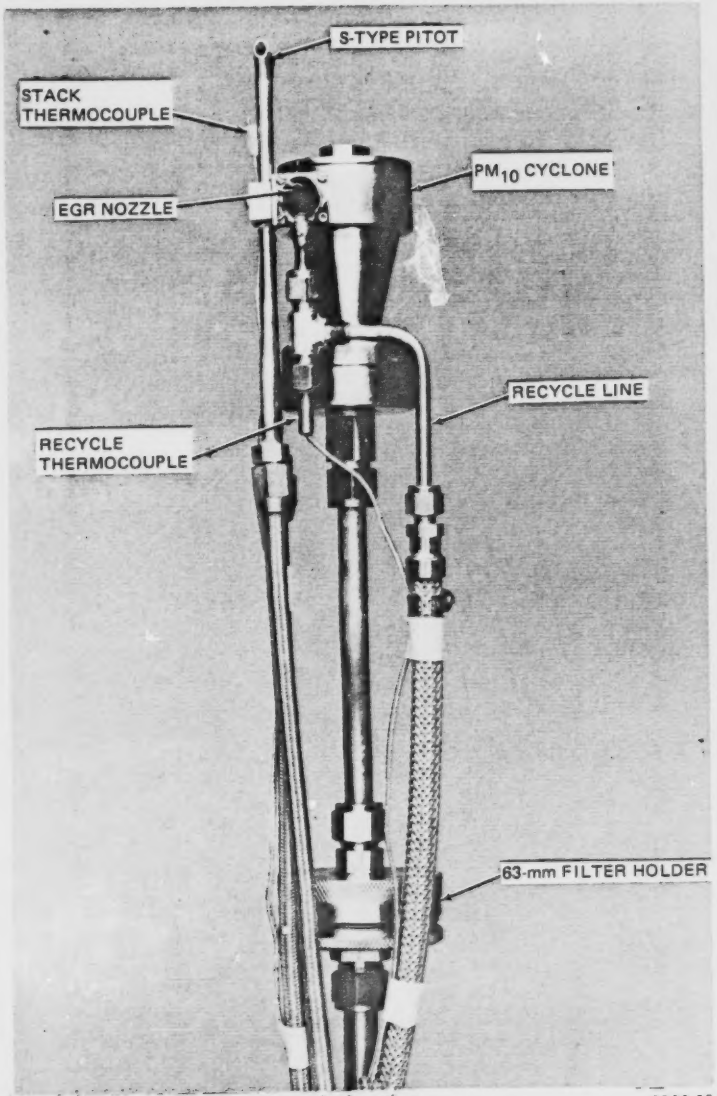
Another important difference betweem CSR protocol and Methods 5 and 17 is the dwell time. In EPA Methods 5 and 17, the dwell time is the same for all traverse points. The measured concentration is a velocity-weighted average for all points, as it should be for determination of emission rate, because the sampling rate is varied at each point in proportion to point velocity. Since flow rate cannot be adjusted from point-to-point with a PM_{10} sampler, the dwell time at each point must be proportional to the stream velocity to obtain a velocity-weighted sample.

Analysis of error due to spatial variation of total particulate emissions versus number of traverse points by Shigehara (1982) indicates that 95% confidence intervals drop rapidly from ±50% for one sample point to less than ±10% at eight or more traverse points. Further analysis indicates that particles smaller than 10 μm are less stratified than total particulate matter, but one site was found in which 12 traverse points were necessary to reduce this type of error below 10%. It is concluded that this type of error would be limited to acceptable levels (below 10%) if the number of traverse points is 8 or 9 when the location of the sample plane is 8 duct diameters downstream and 2 duct diameters upstream from the nearest disturbance as specified by Method 1. Otherwise, 12 traverse points are necessary.

PM_{10} SAMPLERS

Prior to the tests reported here, a prototype EGR train had been constructed by modifications to a commercially available Method 5 sampling train. Cyclone I (Smith and Wilson, 1978), designated SRI/EPA Cyclone I here, was used as the 10-μm size separator, and a recycle (mixing) nozzle was designed and constructed for it. As tests of the prototype were promising (Farthing et al., 1986), two second-generation trains were constructed from individual components incorporating practical improvements and a commercially available version of Cyclone I (Andersen Samplers, Inc., model No.280-1). These two new EGR trains were used in the tests outlined here.

Figure 3-4 is a photograph of the PM_{10} sampler used in these tests with the EGR nozzle. The CSR sampler was like that shown in Figure 3-4 without the EGR nozzle and recycle line. The PM_{10} portion of the catch is that caught on the 63-mm backup filter, outlet tube of the cyclone, and interconnecting tube. The "S" shaped tube connecting the filter holder to the cyclone can be replaced with a cyclone for an additional size fraction such as Cyclone IV (Smith and Wilson, 1978) for a size cut at 2 to 3 μm.



NOTE: See text regarding pitot tube location.

Figure 3-4. PM_{10} cyclone sampling device with EGR nozzle (front view).

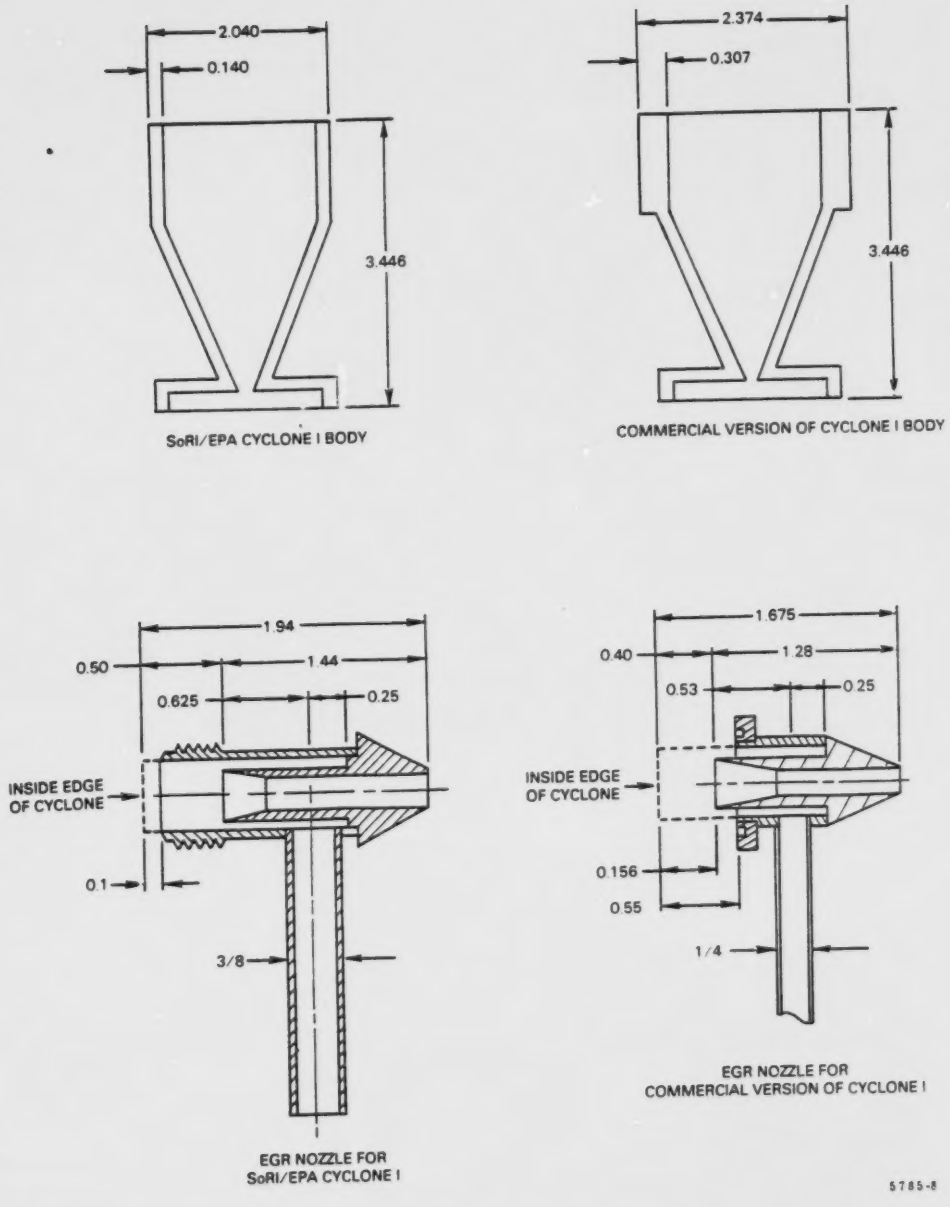


Figure 3-5. Cyclone I bodies and EGR nozzles. All dimensions in inches.

EGR NOZZLES

The EGR nozzle for the commercial version of Cyclone I used in these tests has some differences from that of the original prototype, designed for SRI/EPA Cyclone I, which was used in previous field tests. The purchased cyclones for the EGR systems had a flanged nozzle inlet rather than the original threaded version. Furthermore, although most of the critical inner dimensions of the commercial cyclone were the same as the original design, the cyclone wall thickness had been increased from 0.140 in. to 0.307 in. (see Figure 3-5). Since the PM_{10} package was designed to fit inside a standard 4-in. port, the increase in the wall thickness had the effect of reducing the available nozzle length.

Figure 3-5 also shows the two styles of EGR nozzles designed for each type of cyclone. As previously mentioned, the original prototype EGR nozzle was designed to be threaded into the cyclone body, and the sample core tube did not extend beyond the annular sheath of the recycle gas. It should also be noted that a 3/8-in. diameter tube was used for recycle gas introduction on the original version of the EGR nozzle. Because of the cyclone body changes mentioned above, the EGR nozzle designed to be compatible with the commercial Cyclone I, out of necessity, had to be shorter. Reducing the length of the recycle annulus allowed the system to fit into a 4-in. port, but the sample core tube extended well into the body of the cyclone. If the core tube were shortened to remain completely within the EGR nozzle, it was thought the recycle gas might not form a sufficient annulus within the shorter distance. Therefore, a compromise was made which allowed the sample core tube to be extended slightly (0.156 in.) into the cyclone body, and the diameter of the recycle introduction line was decreased to 1/4-in. This was considered to be sufficient to allow the recycle gas to form a complete annulus and yet provide enough remaining space for adequate mixing before particle separation began in the cyclone.

The nonrecycle nozzles used during the CSR test were the same as that originally designed for the SRI cyclone. These nozzles extend 1.345 in. from the face of the cyclone and taper at 20° from the inlet diameter to 0.5 in. before the inlet to the cyclone. Nozzles with a more abrupt transition were available but not used.

Because of the previously discussed differences in wall thickness between the SRI and commercially available versions of Cyclone I, the nonrecycle nozzles described above, when used with the commercially available Cyclone I, will not fit in a 4-in. port.

SECTION 4

SITE DESCRIPTION

The EGR field test (CP4) and the CSR field test (CP5) were performed during two successive weeks. The same site, a Portland cement plant in northern Alabama, was used for both tests. The tests were conducted at the outlet of a Rexnord gravel bed filter system, which was used to control the emissions from the clinker coolers of two 500-T/day Portland cement kilns. The process consists of introducing a slurry of water and powdered raw materials into a rotating kiln, where calcination forms clinker, which drops onto a moving bed cooler (see Figure 4-1a). Fans blow ambient air through the bed. The bulk of the air from the clinker cooler is used as combustion and secondary air for the kilns. Scavenge air from the system (that air not required by the kiln) is drawn off through the gravel bed filter by the ID fan at the base of the cooler stack (see Figure 4-1b). Plant personnel can adjust flow rates through the gravel bed filter over a limited range by adjusting fan speeds and damper positions. However, large swings in flow rate and temperature occur when the rate of clinker falling into the cooler is erratic.

The sampling area was located approximately 45 ft above ground level on the exhaust stack at the outlet of the gravel bed filter (see Figure 4-2). The circular stack, with an inside diameter of 1.93 m (6 ft 4 in.) was accessible through three 6-in. ports located around the stack in 90° increments. A 3-in. port was also located beside each of the 6-in. ports. Because of the narrow geometry of the sampling platform and walkways, two additional 4-ft. by 8-ft. platforms, for control box placement, were constructed on top of the safety railings on either side of the central walkway. Figure 4-3 shows an overhead view of the sampling area.

Both kilns were operating at full load during the first week of testing (CP4). A power outage and subsequent inability to reestablish proper operation forced shutdown of one kiln near the beginning (after the first three sets of runs) of the second week of testing (CP5). With both kilns on-line, the temperature at the outlet sample location averaged 266 °F with a range of 224 °F to 378 °F and the gas flow rate in the stack ranged from 57,000 acfm (1200 DNCM/min) to 94,000 acfm (1600 DNCM/min). With one kiln on line the temperature averaged 182 °F and ranged from 130 °F to 240 °F and the gas flow rate in the stack ranged from 55,000 acfm (1300 DNCM/min) to 68,000 acfm (1400 DNCM/min). The average and range of stack temperature and velocity for each set of runs are given in Section 5.

The gravel bed filter is constructed on a modular basis, with eight modules making up the system. Each module consists of a cyclonic inlet section followed by two gravel beds operating in parallel. At any one time, during normal operations, seven of the eight modules were on-line in the forward flow direction, while one was being cleaned and renewed by back-flushing with ambient air heated to 150 °F. The modules were cleaned in sequence with a back-flush time of 4.7 min. During the first 45 s of the back-flush period, a mechanical raking system was actuated to stir up the

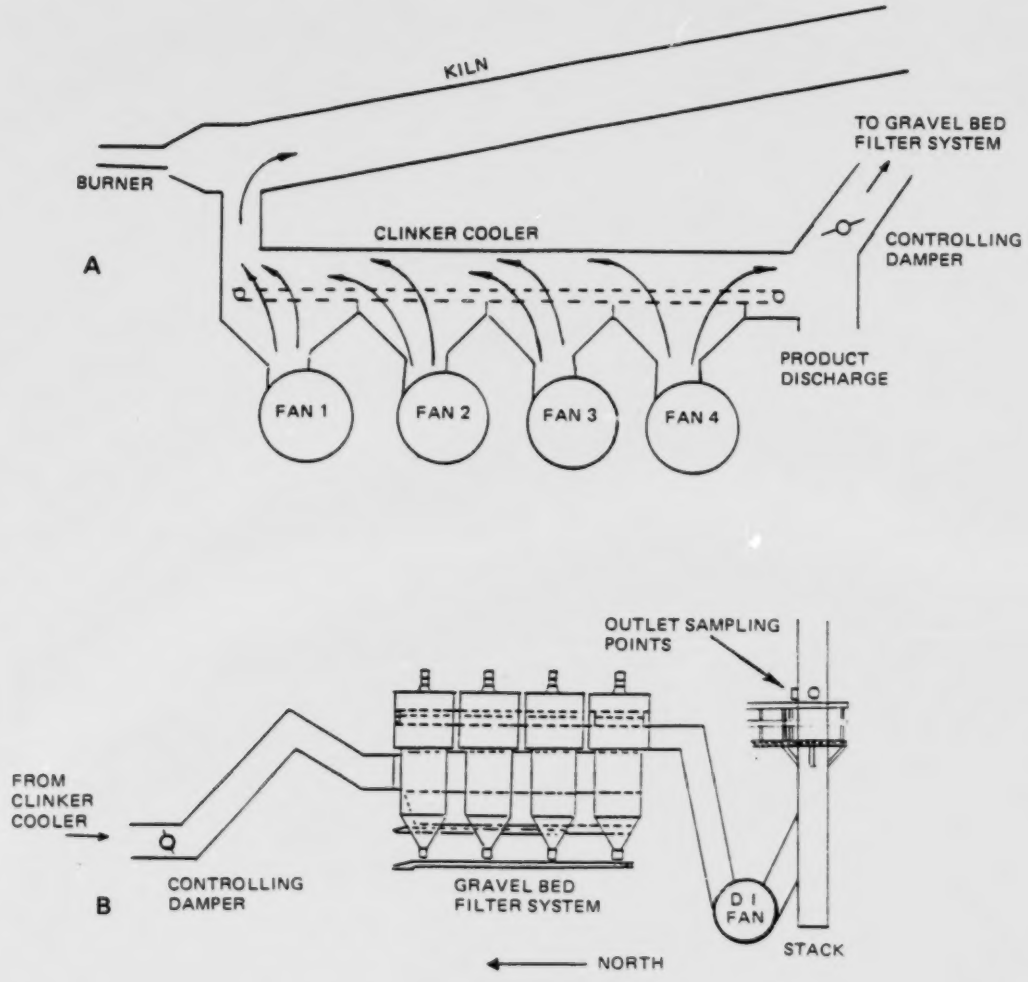


Figure 4-1. Portland cement plant system components. (a) Kiln and clinker cooler layout; arrows indicate directions of airflow. (b) Gravel bed filter system layout and sampling locations.

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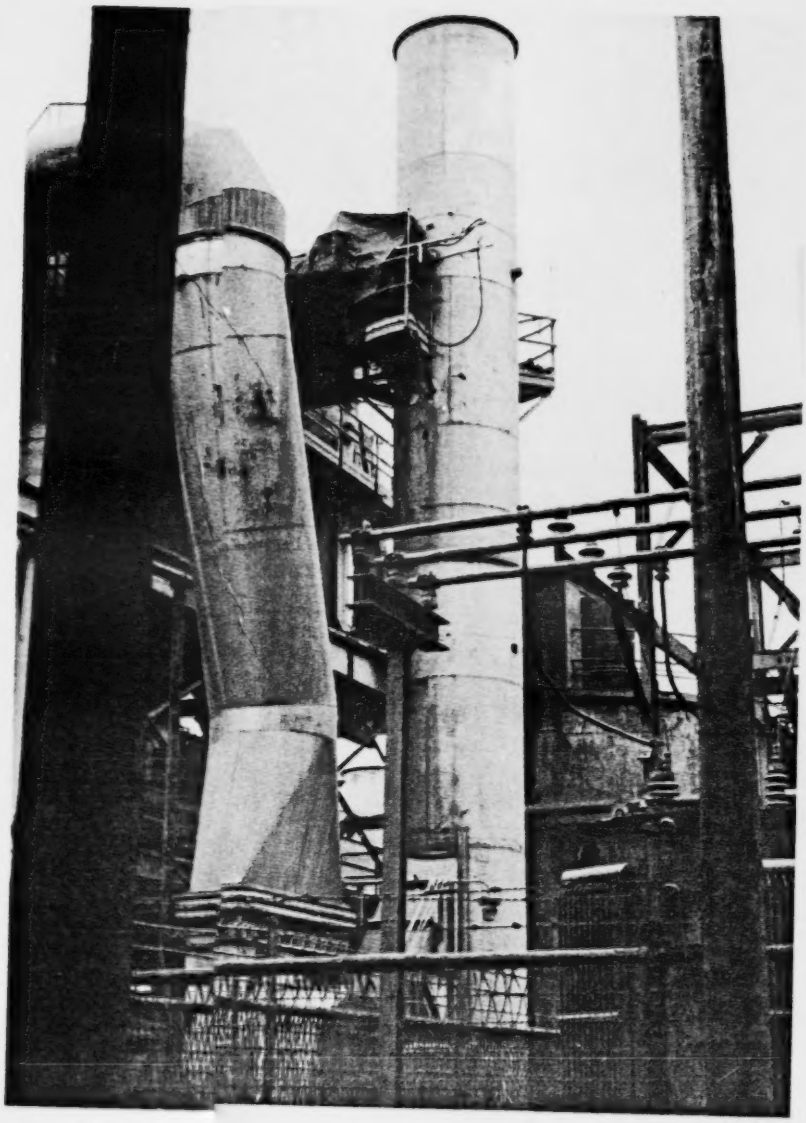

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Figure 4-2. View of stack and sampling platform from the west. The ducting from the gravel bed filter can be seen on the left leading to the ID fan at the bottom of the stack.

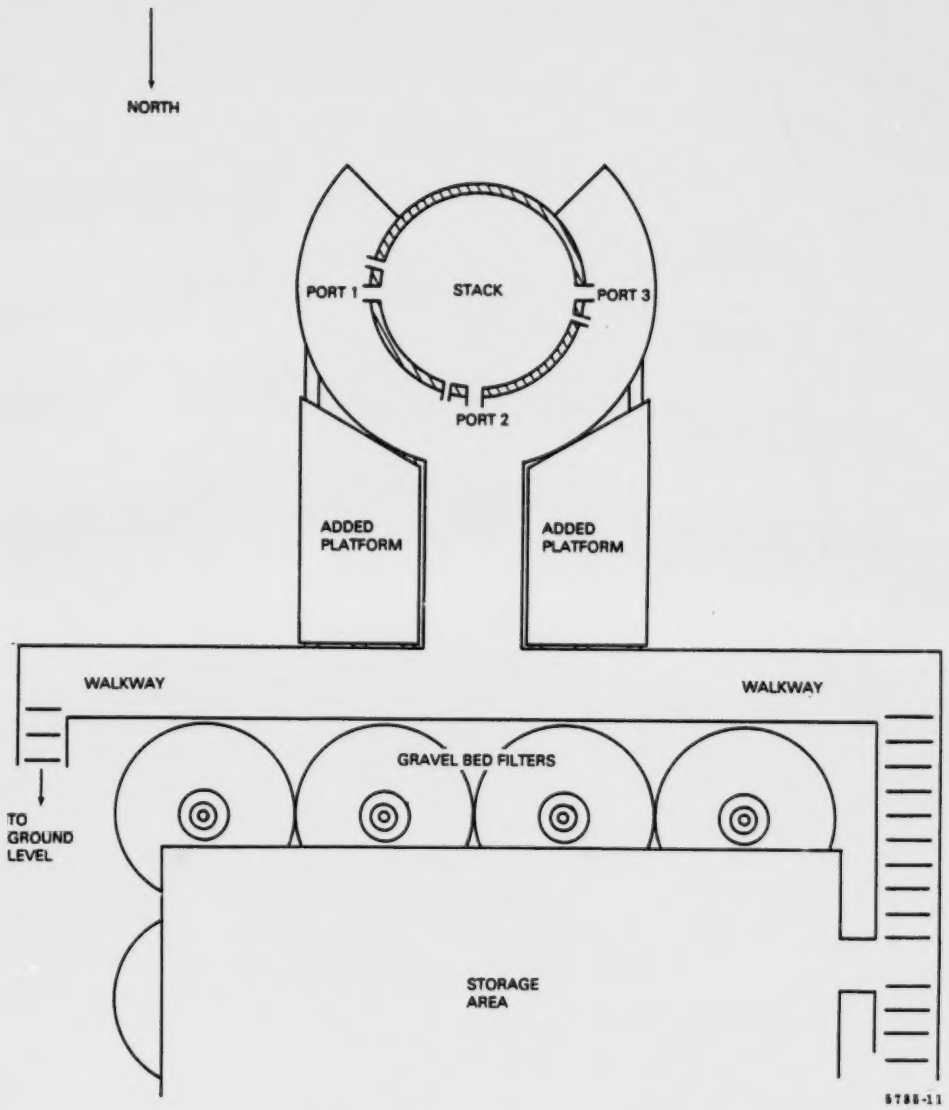

Figure 4-3. Overhead view of sampling area.

dirty gravel. The particle laden air from the module being back-flushed was exhausted into the inlet plenum of the remaining modules. Effects of the cleaning process could be observed at the stack. When the back-flush air changed from one compartment to another, a puff of about 1/2 min duration was usually visible. Stack temperature and velocity head were recorded on a strip chart throughout the test. The temperature dropped about 5 to 10% (in °F) within a matter of seconds, requiring about one minute to recover in an exponential fashion. Pitot readings also showed a spike which lasted from 5 to 10 s.

SECTION 5

TEST PROCEDURES

Test CP4 was designed to evaluate the precision of the EGR sampling system. Thus, two collocated trains were operated simultaneously providing measurements of PM_{10} and total emissions. In addition to precision, the accuracy of the EGR in total emission measurements was evaluated by comparison to Method 17. Through a separate EPA contract, personnel from Entropy Environmentalists, Inc. (Research Triangle Park, NC), simultaneously operated two Method 17 trains collocated with the two EGR trains.

Test CP5 was designed to evaluate the precision of the CSR technique and its comparability with EGR. Thus, two CSR trains and one EGR train were collocated and operated simultaneously. Although the CSR technique is not intended for measurement of total emissions, it was deemed important to continue the Method 17 sampling through test CP5 (the second week). The Method 17 probes were run simultaneously and collocated with the CSR and EGR trains. This provided additional tests of the accuracy of EGR in measurement of total emissions.

For both tests, the PM_{10} samplers consisted of a commercially available Cyclone I (for a particle diameter cut of 10 μm) and a standard 63 mm quartz fiber filter in a stainless steel filter holder as described previously in Section 3. The Method 17 hardware consisted of standard Method 17 sampling systems with "flat pack" filter holders and quartz filters.

All trains were subject to standard quality assurance and quality control procedures. These are described in detail in Section 7.

TEST CP4: PRECISION OF EGR AND ACCURACY FOR TOTAL PARTICULATE MATTER

In test CP4, two identical EGR trains sampled simultaneously with two Method 17 trains, located at the same sampling point (within 5 in.). With the exception of the location of the traverse points, the EGR trains were operated as described by Martin et al. (1988) with upgrades described in Section 2 of this report and the Method 17 trains were operated as specified by EPA Reference Method 17.

The setup of the sampling platform is shown in Figure 5-1. Table 5-1 gives the chronology of the test and port locations of the probes. The EGR trains are designated 1 and 2 and the Method 17 trains A and B. A total of seven sets of comparison runs were completed. One set of Method 17 runs was performed initially without the EGR trains. A break in the weld which attaches the recycle line to the mixing nozzle prevented simultaneous EGR runs. A more substantial weld at the joint solved the problem, and the two EGR trains were prepared for the next set of runs. Run times were 120 min except for the first full set, which was terminated 27 min early because of a power failure. Care was exercised in starting and stopping runs to keep

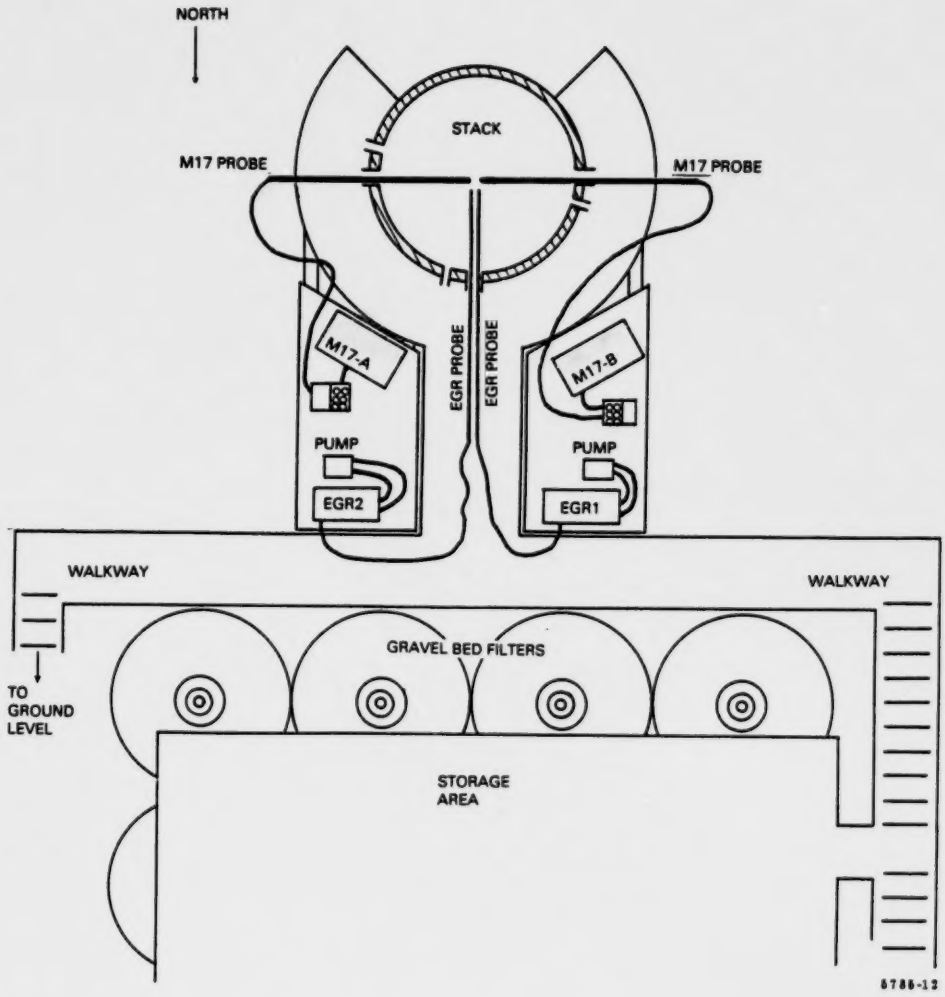

Figure 5-1. Overhead view of sampling area for test CP4.

TABLE 5-1. CHRONOLOGY AND PORT ALLOCATIONS FOR TEST CP4

DAY	TIME	TEST	SAMPLING POSITION
Monday	----	SETUP AND	----
	----	PREPARATIONS	----
Tuesday	1000-1200	M17-A1	PORT 1
		M17-B1	PORT 3
	1645-1818	CP4-1-1	PORT 2 (RIGHT)
		CP4-1-2	PORT 2 (LEFT)
		M17-A2	PORT 1
		M17-B2	PORT 3
Wednesday	1000-1200	CP4-2-1	PORT 2 (RIGHT)
		CP4-2-2	PORT 2 (LEFT)
		M17-A3	PORT 1
		M17-B3	PORT 3
	1459-1659	CP4-3-1	PORT 2 (RIGHT)
		CP4-3-2	PORT 2 (LEFT)
		M17-A4	PORT 3
		M17-B4	PORT 1
Thursday	1020-1220	CP4-4-1	PORT 2 (LEFT)
		CP4-4-2	PORT 2 (RIGHT)
		M17-A5	PORT 3
		M17-B5	PORT 1
	1520-1720	CP4-5-1	PORT 2 (LEFT)
		CP4-5-2	PORT 2 (RIGHT)
		M17-A6	PORT 1
		M17-B6	PORT 3
Friday	0800-1000	CP4-6-1	PORT 2 (LEFT)
		CP4-6-2	PORT 2 (RIGHT)
		M17-A7	PORT 1
		M17-B7	PORT 1
	1230-1310	CP4-7-1	PORT 2 (LEFT)
		CP4-7-2	PORT 2 (RIGHT)
		M17-AB	PORT 3
		M17-B8	PORT 3

all the trains synchronized. Temperature in the stack was monitored with a thermocouple and strip chart so that starting and stopping did not occur during a "puff" due to cleaning of the gravel bed filter.

The positions of the probes were switched, where practical, as indicated in Table 5-1, to account for possible biases due to particulate stratification across the small region(s) around the collocated nozzles. Both Method 17 probes were located in the same port in the last two sets to observe effects associated with relative positions of probes, such as any distortion of gas flow. Figure 5-2 is a photo of the probes in the stack. The two EGR probes are on the left, and one of the Method 17 probes is visible at the right. View of the other Method 17 probe is blocked by the EGR probes.

Gas Velocity and Nozzles

The gas velocity in the stack did not vary significantly with position in the stack. Velocity variation was desired to include the effects of having to adjust nozzle flow rates during the run to maintain isokinetic sampling, as is frequently necessary in Methods 5 or 17. Therefore, plant personnel adjusted the damper at the bottom of the stack during each run to provide three levels of velocity, approximately 33, 40, and 44 ft/s. One third (40 min) of each set of runs was performed at each of the three velocity conditions.

To exclude variations associated with velocity measurement in the evaluation of precision with the EGR technique, the same pitot was used for both trains. It was located between the two cyclones extending 2 in. beyond the end of the cyclone bodies. For operating the Method 17 trains, pitots located on each of these probes were utilized. Before initiating and throughout testing, velocities from all of the pitots were compared to ensure that they agreed satisfactorily. The nozzles chosen for the EGR probes were 3/16 in. in diameter. The nozzles chosen for the Method 17 trains were 0.3 in.

Sample Points

To simulate typical procedures as nearly as possible, traversing of all four probes was performed for the first four sets of runs. A six-point traverse, as shown in Figure 5-3, along the north-south stack diameter was performed. To reach points on this diameter, each Method 17 probe was yawed in the sample plane while the EGR probes simply moved out of port 2. The six traverse points were located 66, 61, 54, 34, and 22 in. from the wall at port 2. Traverse points calculated by Method 1 for this stack were not sampled because the filter holder and part of the cyclone would have been protruding outside of the port. Without additional hardware for maintaining a fixed, known cyclone temperature, the 10-μm cut point could have been compromised. Therefore, sampling points were chosen which kept the PM_{10} samplers inside the port. A stack diameter of 4 ft was assumed, and its center was offset by 6 in. from the actual center of the stack.

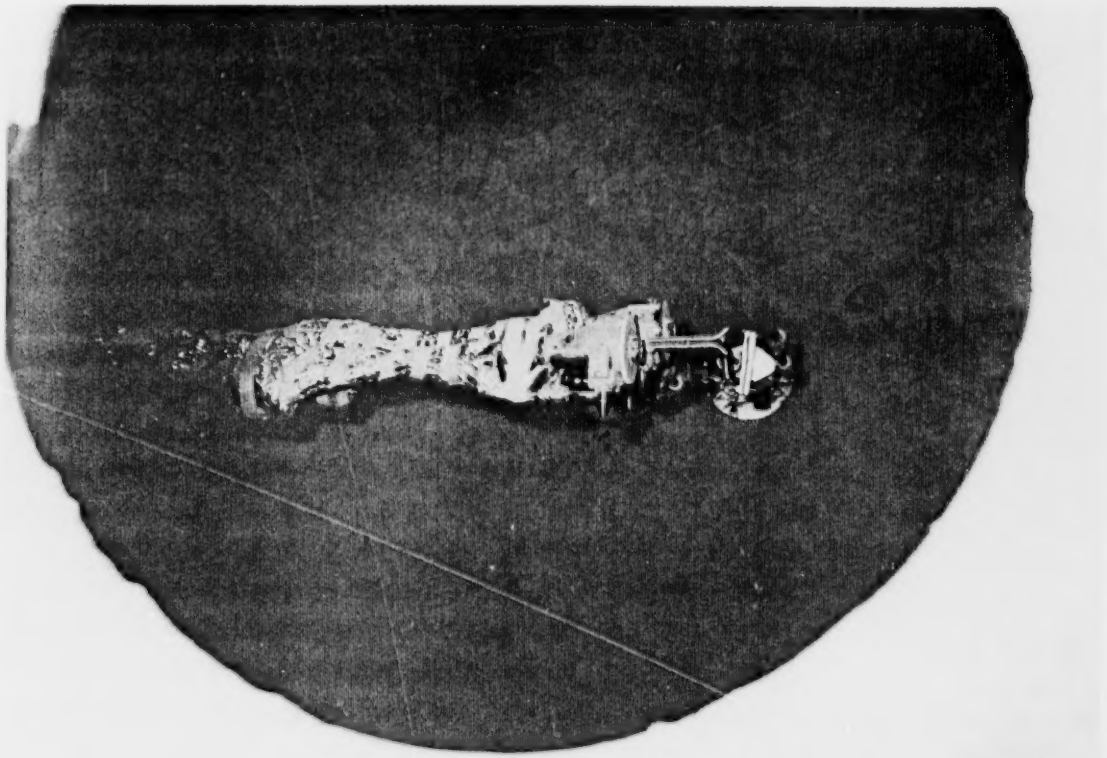

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Figure 5-2. View through port 3 of PM_{10} samplers with EGR nozzles and Method 17 probe.

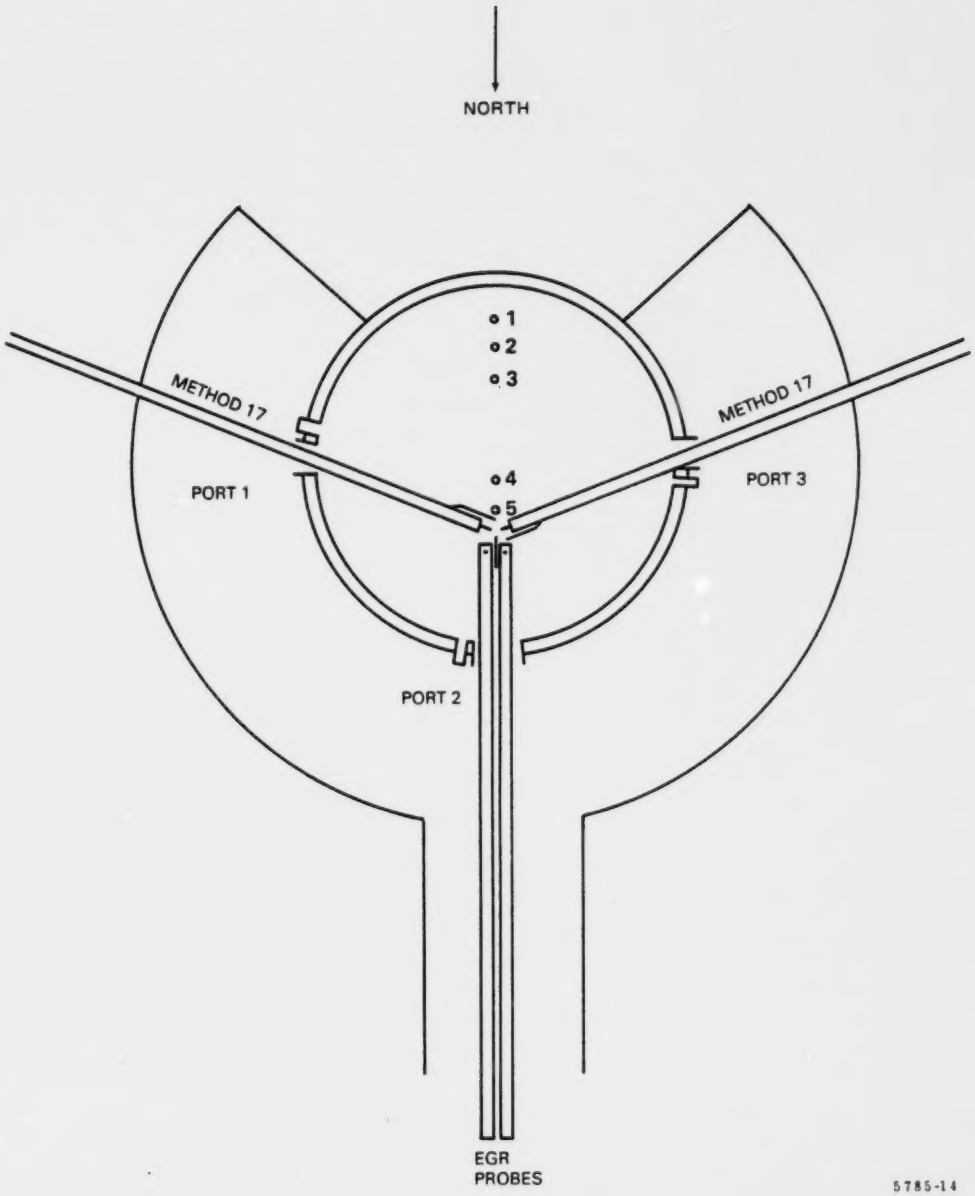


Figure 5-3. Traverse points and probe locations for the 6th point in test CP4.

After three sets of runs, the differences between EGR and Method 17 results were high enough (16%) to cause concern about possible anomalies in the test. To reduce the possibility of distortion of gas flow around the cyclones on the EGR probes, the distance between cyclones was increased from 0.5 in., to 2 in. for subsequent runs. This increased the distance between the two EGR nozzles from 3 in. to 4.5 in. This was accomplished by clamping the out-of-stack ends of the EGR probes together so that the two probes formed a "V".

Four sets of runs were performed while traversing the probes as described above. The last three sets were performed without traversing, sampling only at the center of the stack. Traversing was ceased to eliminate the possibility that the Method 17 probes might preferentially catch dust that was dislodging from the inside walls of the stack because of being closer to the south wall during sampling at the first point. A thick layer of dust was evident all around the inside wall and clumps of dust, about 0.1 in. in diameter, occasionally rained from the stack plume upon the platforms. The layer of dust on the stack wall can be seen in Figure 5-2.

EGR Run Setup

Prior to each test involving the EGR train, the properly sized nozzle was selected, and a data sheet for the calculation of the desired target pressure differentials as a function of stack gas temperature and velocity was prepared. Programs in a spreadsheet format (compatible with Apple II series computers) were written which perform these functions.

The spreadsheet program for selection of the correct EGR nozzle is shown in Figure 5-4. The upper portion of the spreadsheet contains manually entered data concerning the range and average values of pertinent sampling parameters. For a given set of nozzle diameters and the above parameters, the program calculates the isokinetic sample (nozzle) flow rate and the flow rate required through the PM_{10} cyclone to produce a 10-μm cutpoint at each condition. The maximum, average, and minimum percent recycle rate expected across the stack traverse for each nozzle size can be seen near the bottom of Figure 5-4. The operator must choose the nozzle size based on these recycle percentages. If the recycle ratio becomes negative at any of the expected operating conditions, as shown for the 0.25-in. nozzle, the nozzle must be rejected in favor of a smaller diameter nozzle. Similarly, if the recycle ratio is greater than approximately 80%, a larger nozzle should be chosen. The example in Figure 5-4 shows that either the 0.125-in. or the 0.1875-in. nozzle was acceptable. However, the 0.125-in. nozzle shows the higher, less desirable recycle ratios; therefore, for this test series, the 0.1875-in. diameter nozzle was chosen.

Figure 5-5 shows the spreadsheet program for generating the table of target pressure differentials (sample orifice, total flow LFE, and recycle flow LFE) as a function of stack gas temperature and velocity (expressed as pitot ΔP). As with the nozzle selection program, the upper portion of the spreadsheet contains the manual input sampling parameters, along with the EGR system calibrations. The lower portion contains the target pressure

**********EGR INPUT DATA FOR NOZZLE SELECTION **********

	STACK CONDITIONS		EGR SETUP	
PLANT: A CEMENT PLANT	AMB PRESS (IN HG)=	29.65	DH2=	10.98
	DP(STK), (IN H2O)=	.2	TOTAL LFE:	
TEST NO.: EGR1			M=	.2298
RUN NO.: CP4-1-1	NO. PORTS =	1	B=	-.0058
TEST DATE: 10/22/85	NO. PTS PER PORT =	6	RECYCLE LFE:	
TIME: P.M.			M=	.0948
LOCATION: OUTLET	%CO2=	.3	B=	-.0007
	%O2=	21		
STACK DIMENSIONS:	%N2=	78.7	CP(EGR PROBE)=	.83
6.33 FT. DIA.	%H2O	2	VELOCITY RANGE:	
CROSS. AREA (FT2): 31.6	##########	##########	MAX (FPS)=	45
SUBSTRATE ID: NA	M(DRY)=	28.888 #	MIN (FPS)=	25
AMB. TEMP (F)= 75	M(WET)=	28.67 #	AVG (FPS)=	35
	##########	##########		
OPERATOR: S.J. GALLAGHER			STACKP RANGE:	
			MAX (F)=	300
			MIN (F)=	180
			AVG (F)=	220
			NOZ DIA (IN)= NA	

########## CALCULATED RESULTS ##########

STACK TEMP (F)	180	220	300
VISC (MICROPOISE)			
STACK GAS	206	216	237
DRY GAS	208	218	238
FLOWRATES (ACFM)			
0% RECYCLE	.54	.57	.65
100% RECYCLE	.54	.58	.65
NOZZLE ID			
DIAMETER (IN)	.125	.1875	.25
Q SAMPLE (ACFM)			
MAX	.23	.52	.92
AVG	.18	.40	.72
MIN	.13	.29	.51
Q TOTAL (ACFM)			
MAX	.65	.65	.65
AVG	.58	.58	.57
MIN	.54	.54	.54
Q PM10 (ACFM)			
MAX	.65	.65	.65
AVG	.58	.58	.57
MIN	.54	.54	.54
PERCENT RECYCLE			
MAX	80	56	21
AVG	69	30	-25
MIN	57	4	-71

Figure 5-4. Example of EGR nozzle selection spreadsheet.

********** EGR INPUT DATA FOR TARGET RUN PARAMETERS **********

		STACK CONDITIONS		EGR SETUP	
PLANT:	A CEMENT PLANT	AMB PRESS (IN HG)=	29.65	DH2=	10.98
		DP(STK), (IN H2O)=	.2	TOTAL LFE:	0
TEST NO.:	EGR1			M=	.2298
RUN NO.:	CP4-1-1	NO. PORTS =	1	B=	-.0058
TEST DATE:	10/22/85	NO. PTS PER PORT =	6	RECYCLE LFE:	
TIME:	P.M.			M=	.0948
LOCATION:	OUTLET	%CO2=	.3	B=	-.0007
		%O2=	21		
STACK DIMENSIONS:		%N2=	78.7	CP(EGR PROBE)=	.83
	6.33 FT. DIA.	%H2O	2	VELOCITY RANGE:	
CROSS. AREA (FT2):	31.6	################		MAX (FPS)=	40
		M(DRY)=	28.888 #	MIN (FPS)=	20
AMB. TEMP (F)=	75	M(WET)=	28.67 #	AVG (FPS)=	32
DGM TEMP (F)=	90	################			
				STACK TEMP RANGE:	
SUBSTRATE ID:	PANS 501 & 502, CYC FOIL 101, AND			MAX (F)=	300
	FILTER F63-1			MIN (F)=	180
				AVG (F)=	220
OPERATOR:	S.J. GALLAGHER				
				EGR NOZ ID:	EGR 1-2
				NOZ DIA (IN)=	.1835

########## EGR TARGET RUN DATA ################ EGR TARGET RUN DATA ##################

TARGET PRESSURE DIFFERENTIALS (PAGE 1 OF 2)

PITOT DP (IN H20)	DUCT TEMP.(F)=	180	210	240	270	300
.09	DH ORI	.52	.50	.48	.46	.44
	DP TOT	2.06	2.06	2.07	2.08	2.09
	DP REC	3.13	3.18	3.24	3.30	3.36
.11	DH ORI	.66	.63	.60	.58	.55
	DP TOT	2.05	2.06	2.07	2.08	2.09
	DP REC	2.90	2.97	3.03	3.09	3.15
.13	DH ORI	.79	.75	.72	.69	.66
	DP TOT	2.05	2.06	2.07	2.08	2.09
	DP REC	2.70	2.77	2.84	2.91	2.97
.16	DH ORI	.92	.88	.84	.81	.77
	DP TOT	2.05	2.06	2.07	2.07	2.08
	DP REC	2.52	2.59	2.66	2.73	2.80
.18	DH ORI	1.05	1.00	.96	.92	.88
	DP TOT	2.05	2.06	2.06	2.07	2.08
	DP REC	2.35	2.43	2.50	2.57	2.64
.20	DH ORI	1.18	1.13	1.08	1.04	.99
	DP TOT	2.05	2.05	2.06	2.07	2.08
	DP REC	2.19	2.27	2.35	2.42	2.50

########## EGR TARGET RUN DATA ################ EGR TARGET RUN DATA ##################

Figure 5-5. Example of EGR target run parameter spreadsheet (page 1 of 2).

########## EGR TARGET RUN DATA ################ EGR TARGET RUN DATA ##################

TARGET PRESSURE DIFFERENTIALS (PAGE 2 OF 2)

PITOT DP (IN H20)	DUCT TEMP.(F)=	180	210	240	270	300
.22	DH ORI	1.31	1.25	1.20	1.15	1.10
	DP TOT	2.05	2.05	2.06	2.07	2.08
	DP REC	2.04	2.12	2.20	2.28	2.36
.24	DH ORI	1.44	1.38	1.32	1.27	1.22
	DP TOT	2.04	2.05	2.06	2.07	2.08
	DP REC	1.89	1.98	2.06	2.14	2.23
.27	DH ORI	1.57	1.50	1.44	1.38	1.33
	DP TOT	2.04	2.05	2.06	2.07	2.08
	DP REC	1.75	1.84	1.93	2.02	2.10
.29	DH ORI	1.71	1.63	1.56	1.50	1.44
	DP TOT	2.04	2.05	2.06	2.07	2.08
	DP REC	1.62	1.71	1.80	1.89	1.98
.31	DH ORI	1.84	1.75	1.68	1.61	1.55
	DP TOT	2.04	2.05	2.06	2.06	2.07
	DP REC	1.49	1.59	1.68	1.77	1.86
.33	DH ORI	1.97	1.88	1.80	1.73	1.66
	DP TOT	2.04	2.05	2.05	2.06	2.07
	DP REC	1.37	1.47	1.56	1.66	1.75
.36	DH ORI	2.10	2.01	1.92	1.84	1.77
	DP TOT	2.04	2.04	2.05	2.06	2.07
	DP REC	1.25	1.35	1.45	1.55	1.64
.38	DH ORI	2.23	2.13	2.04	1.96	1.88
	DP TOT	2.04	2.04	2.05	2.06	2.07
	DP REC	1.14	1.24	1.34	1.44	1.53
.40	DH ORI	2.36	2.26	2.16	2.07	1.99
	DP TOT	2.04	2.04	2.05	2.06	2.07
	DP REC	1.02	1.13	1.23	1.33	1.43
.42	DH ORI	2.49	2.38	2.28	2.19	2.10
	DP TOT	2.03	2.04	2.05	2.06	2.07
	DP REC	.92	1.02	1.13	1.23	1.33

########## EGR TARGET RUN DATA ################ EGR TARGET RUN DATA ##################

Figure 5-5. Example of EGR target run parameter spreadsheet (page 2 of 2).

differentials. In practice, the operator obtained the stack temperature and pitot ΔP from the collocated thermocouple and pitot tube and determined the appropriate target pressure differentials from the lower section of the spreadsheet. For example, on Figure 5-5, when the stack temperature and ΔP were equal to 240° F and 0.27 in. H_2O, respectively, the target pressure differential for the orifice (ΔH) was 1.44 in. H_2O, the target ΔP for the total LFE was 2.06 in. H_2O, and the target ΔP for the recycle LFE was 1.93 in. H_2O. Since, by definition, the difference between the total and sample flow rates must equal the recycle flow rate, the target ΔP for the recycle LFE serves as an internal system check and, therefore, is not specifically set. If the stack parameters fall between those listed on the run table, the operator simply chooses the nearest parameters and proceeds as above.

EGR Run Data Reduction

As with the setup, a computer spreadsheet program was written for EGR run data reduction (see Figure 5-6). Again, general run parameters were entered in the upper portion of the spreadsheet. The input section also includes average data obtained from the system at each traverse point. The value entered as the average pitot pressure differential at each traverse point is actually the square of the average square root of the pitot ΔP. The results of the data reduction calculations can be seen on the lower section of the reduction spreadsheet (shown here as a separate page). As can be seen, at each traverse point the stack gas velocity, various system flow rates, percent recycle, and isokinetic sampling rate (based on orifice flow rate) were determined. The overall average flow rates, as well as values determined from the dry gas meter, are shown directly below the traverse data. The cut point of the PM_{10} cyclone as determined by the overall total LFE flow rate is also given. Finally, the particulate concentration, in various units, is presented at the bottom of this section.

TEST CP5: PRECISION OF CSR, COMPARABILITY OF CSR AND EGR, AND ACCURACY OF EGR FOR TOTAL PARTICULATE MATTER

In test CP5, two identical CSR trains sampled simultaneously with one EGR train and two Method 17 trains. All probes were collocated (within 6 in.) at the center of the stack. The setup of the sampling platform for test CP5 can be seen in Figure 5-7.

With the exception of the location of traverse points, the CSR runs were performed as described in Section 2. A simulated 12-point traverse was performed; that is, without actually moving the probes, the run was divided into 12 time segments as prescribed by the protocol. The first simulated point (time segment) was arbitrarily set (approximately 10 min). The length of each subsequent time period was directly proportional to the average velocity $(\sqrt{\Delta P})$ at that time relative to the velocity of the initial time period. The total run time was about 120 min but varied somewhat depending upon the temporal variation of duct velocity. The EGR and Method 17 trains were operated as in the previous test (CP4) except they started and stopped

```
***** DATA REDUCTION FOR EXHAUST GAS RECYCLE SAMPLING SYSTEM (VERSION 2.1, 11-22-85 *******
*                              ---- RUN PARAMETERS ----      ---- GAS ANALYSIS ----        *
* PLANT: A CEMENT PLANT        AMB PRES (IN HG) = 29.65      %CO2 =              .3        *
* TEST ID:    CP4              STK DP (IN H2O) =     .2      %O2 =               21        *
* RUN ID:     1-1                                          ## %N2 =          78.7  ###    *
* TEST DATE:  10-22-85         AMB TEMP (F) =        79                                   *
* TIME:       16:45                                                                      *
* LOCATION:   CLINKER COOLER   NO. PORTS =            1     ESTIMATE % H2O =     0        *
*             OUTLET           NO. PTS PER PORT =     5         -OR-                      *
*                                                          VOLUME H2O                     *
*                                                          COLLECTED (ML) =  12.3         *
*                              SUBSTRATE ID:               ############################   *
* ----SAMPLING SYSTEM ---            CY 101, F63-1,        ## DRY MW =       28.89  ##   *
* SAMPLER ID: EGR-1                  PANS 501 & 502        ############################   *
* ORIENTATION: HORIZONTAL                                                                 *
*                                                          ---- COLLECTED MASS (MG) ---   *
* DH@ =  10.55                 NOZZLE DIA (IN) =  .1835     CYCLONE I CATCH =       75.3  *
*                                                          CYCLONE I WASH =         2.5  *
* GAMMA=  .994 DGM             SAMPLE TIME (MIN)=    93                                   *
*                                                          FILTER CATCH =          46.85 *
* TOTAL LFE:                   DGM (INIT, FT3) =  60.50    FILTER WASH =           12.4  *
*    M = .2298                 DGM (FINAL, FT3) = 89.86                                   *
*    B = -.006                                            WASH BLANK =               0  *
* RECYCLE LFE:                 OPERATORS:                  FILTER BLANK =             0  *
*    M = .0948                       S.J. GALLAGHER                                       *
*    B = -7E-4                                                                            *
* PITOT                                                                                   *
*   CP =   .83                                                                            *
*                              TRAVERSE DATA (IN H2O & DEG F)                             *
*                                                                                         *
*       PORT/    DP   DH    DP     P    DP   TEMP  TEMP  TEMP    TEMP TEMP               *
*       POINT  PITOT SAMP  TOTAL INLET  RCL   STK   RCL  PROBE   LFE  DGM               *
*                                                                                         *
*    1  2/1     .45  2.25  2.08  6.15  1.35   268   268   270     89   90               *
*    2  2/2     .49  2.28  2.10  5.96  1.27   296   296   267     94   90               *
*    3  2/3     .37  1.74  2.10  8.44  1.78   293   295   265     97   91               *
*    4  2/4     .21  1.24  2.10  7.02  2.36   286   289   265     98   91               *
*    5  2/5     .35  1.64  2.10  5.53  1.93   289   288   266     98   .92              *
*    6                                                                                    *
*    7                                                                                    *
*    8                                                                                    *
*    9                                                                                    *
*   10                                                                                    *
*   11                                                                                    *
*   12                                                                                    *
*   13                                                                                    *
*   14                                                                                    *
*   15                                                                                    *
*   16                                                                                    *
*   17                                                                                    *
*   18                                                                                    *
*   19                                                                                    *
*   20                                                                                    *
*****************************************************************************************
```

Figure 5-6. Example of EGR data reduction spreadsheet (page 1 of 2).

```
########################################## RESULTS ##############################################
# TEST ID: CP4                                                                                  #
# RUN ID: 1-1                                                                                   #
#                                                                                               #
# STACK GAS MOISTURE CONTENT:                                                                   #
# SAMPLE VOLUME (DSCF)=  27.853                                                                 #
# PERCENT H2O (STK)=      2.04                                                                  #
#                                                                                               #
#       PORT/      STACK      SAMPLE      RECYCLE      TOTAL      APPROX.    APPROX.           #
#       POINT      VELOCITY   (ORIFICE)   FLOW RATE    FLOW RATE  PERCENT    PERCENT           #
#                             FLOW RATE                          RECYLE     ISOK'TIC          #
#                  FPS        ACFM        ACFM         ACFM                                    #
#                                                                                               #
#    1  2/1          44          .48          .17          .62        23         100            #
#    2  2/2          47          .50          .16          .65        22          98            #
#    3  2/3          41          .44          .22          .64        32          98            #
#    4  2/4          31          .36          .29          .63        42         108            #
#    5  2/5          39          .42          .24          .63        33          98            #
#    6                0            0            0            0         0           0            #
#    7                0            0            0            0         0           0            #
#    8                0            0            0            0         0           0            #
#    9                0            0            0            0         0           0            #
#   10                0            0            0            0         0           0            #
#   11                0            0            0            0         0           0            #
#   12                0            0            0            0         0           0            #
#   13                0            0            0            0         0           0            #
#   14                0            0            0            0         0           0            #
#   15                0            0            0            0         0           0            #
#   16                0            0            0            0         0           0            #
#   17                0            0            0            0         0           0            #
#   18                0            0            0            0         0           0            #
#   19                0            0            0            0         0           0            #
#   20                0            0            0            0         0           0            #
#                                                                                               #
# AVERAGES:          40          .44          .21          .63        30         100            #
#                                                                                               #
# SAMPLE FLOW RATE=   .44 ACFM (FROM DGM)                                                       #
# PERCENT RECYCLE=     31                                                                       #
# % ISOKINETIC=        98                                                                       #
# STACK TEMP (F)=     286                                                                       #
#                                                                                               #
# CYCLONE 1 SIZE CUT:                                                                           #
# VISCOSITY @ CYC=    235 MICROPOISE                                                            #
# CUT DIAMETER=     10.06 MICRON                                                                #
#                                                                                               #
# PART. CONCENTRATIONS:   GR/ACF     GR/DSCF     LB/DSCF      MG/DNCM   PERCENT OF TOTAL      #
#                                                (X 1E6)                                        #
# LARGER THAN 10 MICRONS: .0296        .0430       6.16         98.64        57                #
# LESS THAN 10 MICRONS:   .0225        .0328       4.69         75.12        43                #
#                                                                                               #
# TOTAL LOADING:          .0521        .0758      10.85        173.76                           #
#                                                                                               #
#################################################################################################
```

Figure 5-6. Example of EGR data reduction spreadsheet (page 2 of 2).

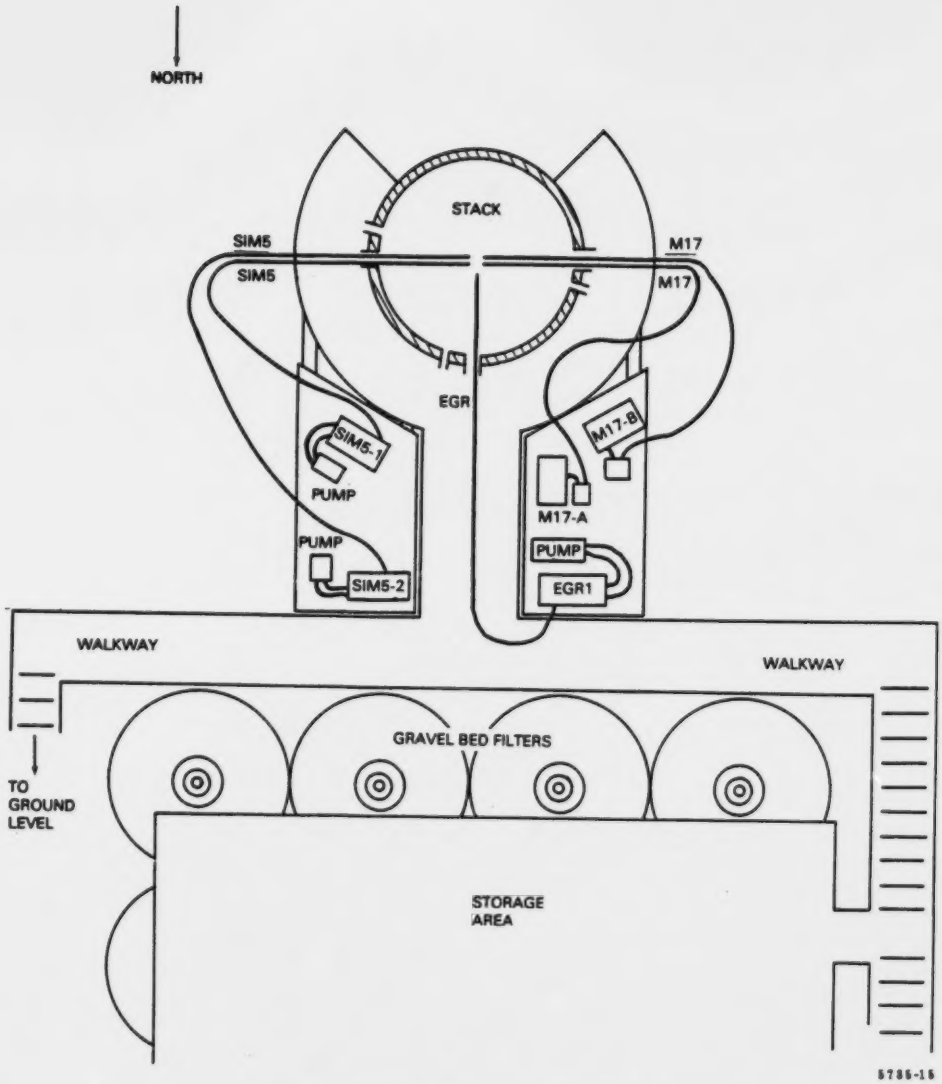


Figure 5-7. Overhead view of sampling area for test CP5.

precisely with the CSR trains. As with the runs in the previous test, the run time was also adjusted slightly to avoid starting or stopping in the minute just after the gravel bed filter started cleaning a compartment.

Table 5-2 gives the port location of the probes and chronology for each set of runs in this test. The CSR probes are denoted S1 and S2. As in the previous test, the north port (no. 2) was used for the EGR probe in all sets. The CSR probes sampled together through the same port during each set as did the Method 17 probes. The CSR and Method 17 probes were switched between ports 1 and 3 between sets of runs. Figure 5-8 is a labeled photo of the five probes viewed from the east side of the stack.

A total of nine replicate run sets (two CSR, one EGR, and two Method 17 trains) were successfully completed during CP5. One set of Method 17 runs was performed initially without the CSR or EGR trains. The last CSR run with train 1 was invalid because of a torn pump hose (positive side). The last Method 17 run with train A was stopped several minutes before the other trains because of the breakage of an impinger.

Gas Velocity and Nozzles

It was expected that stack velocity would be varied substantially (33 to 44 ft/s), as in the previous test through variation of the damper at the ID fan at the base of the stack. However, as described in Section 4, a power outage and the subsequent inability to stabilize one kiln caused it to be taken off line. With one kiln the damper could not be varied. Thus, only the first two sets of runs had the anticipated variation of gas velocity, whereas the remaining seven runs did not. The first three sets of runs were performed with two kilns operating and the last six sets with one kiln in operation.

During runs, pitot measurements for the EGR and Method 17 trains were the same as in test CP4. Agreement between pitots on the EGR and Method 17 probes was verified throughout this test. To reduce congestion in the stack at the sample point, pitots were not installed on the CSR probes. Pitot readings for CSR purposes were obtained from the Method 17 (train A).

The nozzles chosen for CSR runs were changed several times through the test in an attempt to minimize anisokinetic sampling. Two sizes were utilized, 0.21 and 0.24 in. although the CSR protocol would have permitted either nozzle during any of the runs. The same nozzles from the previous test were used for the EGR and Method 17 probes.

CSR Run Setup

The CSR protocol requires a series of setup and reduction calculations; therefore, as an aid to the operator a computer (Apple II series) spreadsheet program was written which performs these calculations. Although the setup and reduction programs are combined on a single spreadsheet, for clarity they are described here individually.

TABLE 5-2. CHRONOLOGY AND PORT ALLOCATIONS FOR TEST CP5

DAY	TIME	TEST	SAMPLING POSITION
Monday	AM	M17-A9	PORT 1
		M17-B9	PORT 3
	1522-1730	CP5-1-S1	PORT 1 (LEFT)
		CP5-1-S2	PORT 1 (RIGHT)
		CP5-1-EGR1	PORT 2
		M17-A10	PORT 3 (RIGHT)
		M17-B10	PORT 3 (LEFT)
Tuesday	1033-1233	CP5-2-S1	PORT 3 (LEFT)
		CP5-2-S2	PORT 3 (RIGHT)
		CP5-2-EGR1	PORT 2
		M17-A11	PORT 1 (RIGHT)
		M17-B11	PORT 1 (LEFT)
	1624-1758	CP5-3-S1	PORT 1 (RIGHT)
		CP5-3-S2	PORT 1 (LEFT)
		CP5-3-EGR1	PORT 2
		M17-A12	PORT 3 (RIGHT)
		M17-B12	PORT 3 (LEFT)
Wednesday	1013-1213	CP5-4-S1	PORT 1 (RIGHT)
		CP5-4-S2	PORT 1 (LEFT)
		CP5-4-EGR1	PORT 2
		M17-A13	PORT 3 (RIGHT)
		M17-B13	PORT 3 (LEFT)
	1511-1710	CP5-5-S1	PORT 3 (RIGHT)
		CP5-5-S2	PORT 3 (LEFT)
		CP5-5-EGR1	PORT 2
		M17-A14	PORT 1 (RIGHT)
		M17-B14	PORT 1 (LEFT)
Thursday	0945-1248	CP5-6-S1	PORT 1 (RIGHT)
		CP5-6-S2	PORT 1 (LEFT)
		CP5-6-EGR1	PORT 2
		M17-A15	PORT 3 (RIGHT)
		M17-B15	PORT 3 (LEFT)
	1524-1730	CP5-7-S1	PORT 3 (RIGHT)
		CP5-7-S2	PORT 3 (LEFT)
		CP5-7-EGR1	PORT 2
		M17-A16	PORT 1 (RIGHT)
		M17-B16	PORT 1 (LEFT)
Friday	0843-1044	CP5-8-S1	PORT 3
		CP5-8-S2	PORT 3
		CP5-8-EGR1	PORT 2
		M17-A17	PORT 1 (RIGHT)
		M17-B17	PORT 1 (LEFT)
	1407-1610	CP5-9-S1	PORT 1 (RIGHT)
		CP5-9-S2	PORT 1 (LEFT)
		CP5-9-EGR1	PORT 2
		M17-A18	PORT 3 (RIGHT)
		M17-B18	PORT 3 (LEFT)

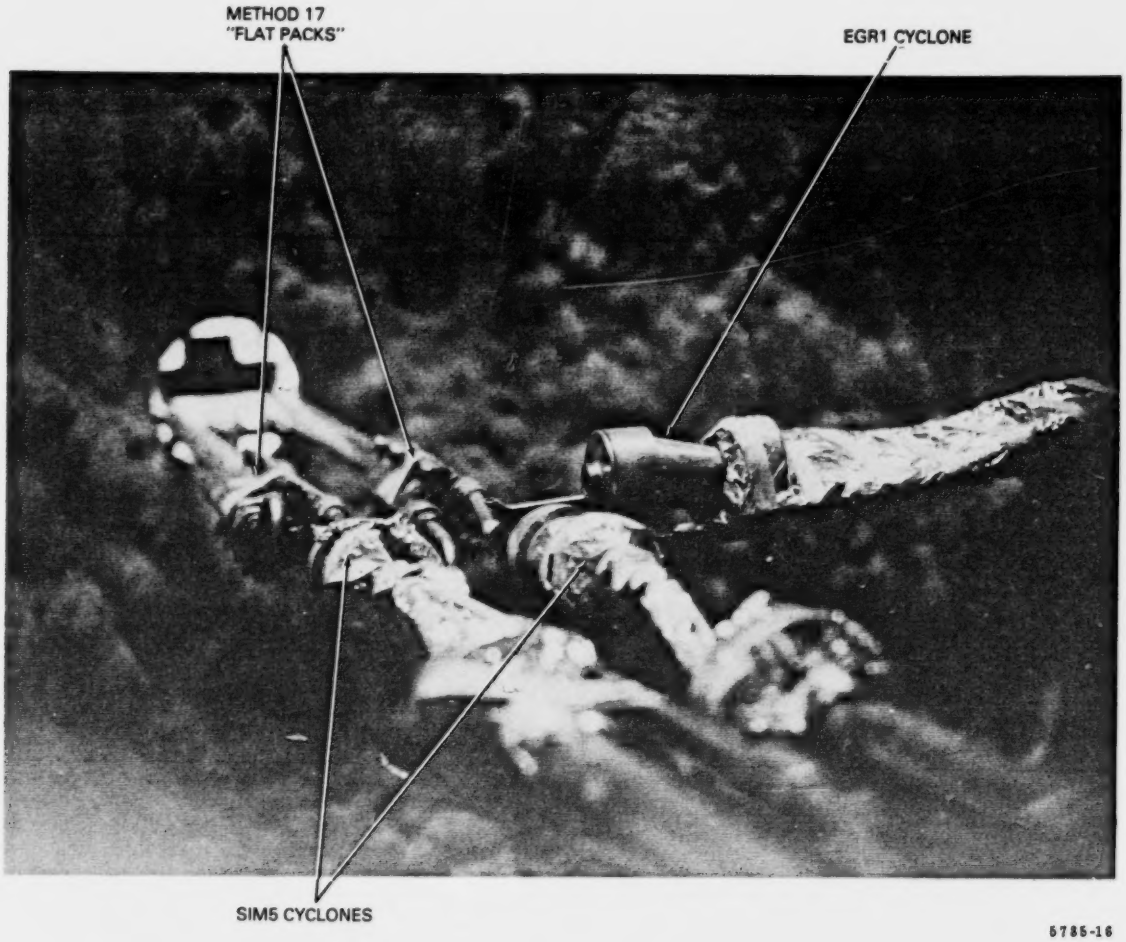


Figure 5-8. View through 3-in. port on east side of stack showing PM_{10} samplers and Method 17 probes.

Figure 5-9 shows the setup spreadsheet for the CSR protocol. The setup section of the spreadsheet is divided roughly into three pages. The first page contains manually input data such as plant specific information, gas composi- tion, stack conditions, system calibrations, and Method 2 temperature and pitot ΔP information. The second page determines the PM_{10} flow rate at the average stack conditions, displays the limits for a given set of nozzle diameters, translates the Method 2 data to reflect system values, and produces a table of PM_{10} flow rates as a function of stack gas temperature. The final page produces a run table for the operator to record pitot pressure differentials and dwell times for each sampling point. Also, the equation to determine the dwell time at each point is displayed.

CSR Run Data Reduction

As mentioned above, the CSR data reduction program is actually combined into a single spreadsheet, along with the setup program. The data reduction section can be seen in Figure 5-10. The top portion of the reduction program contains input data specific to each run (i.e., sample volume, water content, mass loadings, etc.). The lower section displays the calculated results from a given test run. The dwell time and pitot pressure differential for each point are entered on the setup portion of the spreadsheet immediately prior to the reducing the data. These values may then serve as the Method 2 data for the subsequent run. The size-segregated particulate loading concentrations can be seen at the bottom of the data reduction form.

SAMPLE RECOVERY

After each test run, the cyclone trains were unloaded in the on site laboratory by SRI personnel. The particulate matter collected on the inside walls and in the collection cup of the nozzle and cyclone body were carefully brushed, by using a #6 or #7 camel hair brush, into a uniquely marked, preweighed foil pouch. The same surfaces were then washed with approximately 20 mL of reagent-grade acetone. These rinses were then placed into individual foil dishes, and the acetone was allowed to evaporate, leaving the residue trapped in the preweighed foil dishes. The 63-mm filter, along with a pair of Teflon® gaskets, and any particulate matter which could be brushed from the inside surfaces of the filter holder and Cyclone I exit tube were also placed in a uniquely marked, preweighed foil pouch. Finally, the exit tube from Cyclone I and the appropriate inside surfaces of the filter holder were rinsed into another foil evaporating dish with 40 to 60 mL of reagent-grade acetone. The greater amount of particles collected inside the exit tube required the use of more rinse reagent than that of the cyclone itself. This second rinse was evaporated, as the first, over a warm hot plate. Each sample was then placed in an individual Petri dish, which was in turn placed in a silica gel desiccator until the sample could be weighed. The samples were weighed by using an electronic analytical balance on-site at least once, and the weighings were repeated at SRI laboratories.

******* INPUT DATA FOR METHOD 2 AND CSR SETUP OR REDUCTION **********

METHOD 2 (VELOCITY TRAVERSE)			CSR SETUP	
PLANT: A CEMENT PLANT	AMB PRESS (IN HG)=	29.2	T(DGM), (F)=	64.2
	DP(STK), (IN H2O)=	.2	DH@=	5.068
TEST NO.: CSR (TEST 5)	CP(VEL PROBE) =	.84	CP (CSR PROBE) =	.84
RUN NO.: CP5-4-S2	NO. PORTS =	2		
SUBSTRATE ID: CY FOIL 126	NO. PTS PER PORT =	6	SAMPLE TIME (MIN)=	119.5
PANS 551 & 552, F63-27	%CO2=	.3	NO. POINTS:	12
TEST DATE:10/30/85	%O2=	21		
TIME: 10:13	%N2=	78.7	STACK TEMP RANGE :	
LOCATION: OUTLET OF	%H2O=	2	MAX (F) =	250
CLINKER COOLER FILTER	##########	##########	MIN (F) =	100
STACK DIMENSIONS:	# M(DRY)=	28.89 #		
6.33 FT. DIA	# M(WET)=	28.67 #		
CROSS. AREA:	##########	##########	AMB. TEMP (F)=	63
31 SQ. FT.				

********** INPUT METHOD 2 OR CSR DATA **********

TRAV. PT.		PORT 1	PORT 2	PORT 3	PORT 4	SUMS
1	PITOT DP	.312	.286			1.09
	STACK TEMP	141	131			272
	DWELL TIME	10	9.5			27
2	PITOT DP	.327	.312			1.13
	STACK TEMP	135	130.5			266
	DWELL TIME	10.25	10			28
3	PITOT DP	.311	.286			1.09
	STACK TEMP	130.5	130.5			261
	DWELL TIME	10.25	9.75			27
4	PITOT DP	.312	.287			1.09
	STACK TEMP	131	127.5			259
	DWELL TIME	10	9.75			27
5	PITOT DP	.326	.295			1.11
	STACK TEMP	136	133			269
	DWELL TIME	10.25	10			27
6	PITOT DP	.311	.285			1.09
	STACK TEMP	134	153			287
	DWELL TIME	10	9.75			27
7	PITOT DP					0.00
	STACK TEMP					0
	DWELL TIME					0
8	PITOT DP					0.00
	STACK TEMP					0
	DWELL TIME					0

AVERAGES: STACK TEMP (F)= 134 SQRT(DP)= .55
STACK VEL (FPS)= 33

Figure 5-9. Example of CSR setup spreadsheet (page 1 of 3).

```
################## CSR SETUP ################# CSR SETUP ##########################
*      NEW RUN ID: CP5 5-S2          *
************************************
    VISCOSITY (MICROPOISE)=       195
    PM10 FLOW RATE (ACFM)=         .50  ****************************
    VISC**SQRT (FLOWRATE)=         735, ROUND UP TO:           750  *
                                        ****************************
          NOZZLES:        1         2         3         4
******** NOZ. ID       FC1-9     FC1-8     FC1-7          ********
******** DIA (IN)      .1933     .2042     .2368          ********
######## NOZ. VEL.        41        37        27     ERROR ########

********* INPUT MINIMUM & MAXIMUM VELOCITIES FROM NOMOGRAPH *********************
          MIN. VEL:     30.5      24.8      16.7
          MAX. VEL:     62.5      54.1      45.3
*****************************************************************************
DP LIMITS FOR PITOT OF CSR PROBE:
     MIN, DP(LL):        .25       .17       .08      0.00
     MAX, DP (UL):      1.07       .80       .56      0.00
           (CP'/CP)^2 =     1          (PREVIOUS/CURRENT PITOT)

 COMPARE DP(LL) AND DP(UL) TO EXPECTED DP'S BELOW AND CHOOSE NOZZLE(S).
                 PORT 1              PORT 2              PORT 3              PORT 4
                -------------       --------------      --------------      --------------
TRAV. PT      DP      NOZ ID      DP      NOZ ID      DP      NOZ ID      DP      NOZ ID

   1          .312    FC1-7       .286    FC1-7          0                   0

   2          .327                .312                   0                   0

   3          .311                .286                   0                   0

   4          .312                .287                   0                   0

   5          .326                .295                   0                   0

   6          .311                .285                   0                   0

   7            0                   0                    0                   0

   8            0                   0                    0                   0

        ORIFICE PRESSURE DROP (DH):AN ITERATIVE SOLUTION IS PERFORMED.  THE
        INDEX BELOW SHOULD BE SET TO 1 TO START THE ITERATION AND THEN CHANGED
        TO A VALUE GREATER THAN 1 FOR THE ITERATION TO CONTINUE AUTOMATICALLY
        DURING EACH RECALCULATION.
      *************************
      *  INDEX =   2          *
      *************************
    STACK TEMP (F)=              100       138       175       213       250
    VISCOSITY (MICROPOISE)=      187       196       205       215       224
    PM10 FLOW RATE (ACFM)=       .47       .50       .54       .57       .61
    INITIAL DH (IN H2O)=        1.64      1.65      1.66      1.67      1.69
    PRESSURE AT DGM=           29.32     29.32     29.32     29.32     29.32
    FINAL RUN DH (IN H2O)=      1.64      1.65      1.66      1.67      1.69
################## CSR SETUP ################# CSR SETUP ##########################
```

Figure 5-9. Example of CSR setup spreadsheet (page 2 of 3).

########## CSR RUN PARAMETERS ################## CSR RUN PARAMETERS ##################

****
* NEW RUN ID:CP5 5-S2 *
****

	NOZZLES 1	2	3	4	
LIMITS OF PITOT DP:					
DIA (IN)	.1933	.2042	.2368	0	
DP(LL), (IN H2O)	.25	.17	- .08	0.00	
DP(UL), (IN H2O)	1.07	.80	+ .56	0.00	
ORIFICE PRESSURE DROP (DH):					
STACK TEMP (F) =	100	137.5	175	212.5	250
DH (IN H2O)=	1.64	1.65	1.66	1.67	1.69

DWELL TIMES T(N):

T(N) = (T(1)/SQRT(DP(1)))*SQRT(DP(N) = $18.4\sqrt{DP_n}$

	PORT 1		PORT 2		PORT 3		PORT 4	
TRAV PT	DP	TIME	DP	TIME	DP	TIME	DP	TIME
1	~~0.295~~ .312	~~10~~ 10.09	0.268	9½				
2	0.31	10¼	0.30	10¼				
3	0.28	9¾	0.29	10				
4	0.275	9¾	0.27	9½				
5	0.305	10¼	0.25	9¼				
6	0.29	10	0.26	9½				
7								
8								

Figure 5-9. Example of CSR setup spreadsheet (page 3 of 3).

********** INPUT DATA FOR CSR DATA REDUCTION **********

RUN ID: CP5 4-S2

VOL(FIN), (FT^3) =	157.382	CYCLONE CATCH, MG=	75.8
VOL(INIT),(FT^3) =	104.978	CYCLONE WASH, MG =	3.1
DGM GAMMA=	.99997	FILTER CATCH, MG =	79.85
T(DGM), (F) =	64.2	FILTER WASH, MG =	13.4
VOL(H2O), (ML) =	14.54	ACETONE BLANK, MG=	0
AVG DH (IN H2O)=	1.63	FILTER BLANK, MG =	0
SAMPLE TIME (MIN)=	119.5	TOTAL, MG =	172.15
NOZZLE DIA. =	.2352		

********** RESULTS **********

VOL(METER), DSCF =	51.72	SAMPLER FLOWRATE BY DGM =	.51 ACFM
		NOZZLE VELOCITY BY DGM =	28 FPS
% MOISTURE =	1.31	AVERAGE DUCT VELOCITY =	33 FPS
STACK TEMP (F)=	134		
M(DRY)=	28.89	AVE. NOZZLE/AVE. DUCT VELOCITY (%) =	84
M(WET)=	28.75		
VISCOSITY (STACK)=	196	SAMPLER CUT SIZE =	9.94 MICRONS

TRAV. PT.		PORT 1	PORT 2	PORT 3	PORT 4	SUMS
1	DWELL TIME (MIN)	10	9.5	0	0	
	STREAM VEL (FPS)	34	32	0	0	
	% ISOKINETIC	82	87	NA	NA	16
2	DWELL TIME (MIN)	10.25	10	0	0	
	STREAM VEL (FPS)	35	34	0	0	
	% ISOKINETIC	81	83	NA	NA	17
3	DWELL TIME (MIN)	10.25	9.75	0	0	
	STREAM VEL (FPS)	34	32	0	0	
	% ISOKINETIC	83	87	NA	NA	17
4	DWELL TIME (MIN)	10	9.75	0	0	
	STREAM VEL (FPS)	34	32	0	0	
	% ISOKINETIC	83	87	NA	NA	17
5	DWELL TIME (MIN)	10.25	10	0	0	
	STREAM VEL (FPS)	35	33	0	0	
	% ISOKINETIC	81	85	NA	NA	17
6	DWELL TIME (MIN)	10	9.75	0	0	
	STREAM VEL (FPS)	34	33	0	0	
	% ISOKINETIC	83	85	NA	NA	17
7	DWELL TIME (MIN)	0	0	0	0	
	STREAM VEL (FPS)	0	0	0	0	
	% ISOKINETIC	NA	NA	NA	NA	0
8	DWELL TIME (MIN)	0	0	0	0	
	STREAM VEL (FPS)	0	0	0	0	
	% ISOKINETIC	NA	NA	NA	NA	0
TIME AVERAGE OF % ISOKINETIC =			84			

CONCENTRATIONS:	GR/ACF (X 1E-3)	GR/DSCF (X 1E-3)	LB/DSCF (X 1E-6)	MG/DNCM	MG/DSCF	FRACTION
GREATER THAN 10 um	20.11	23.49	3.36	53.87	1.53	.46
LESS THAN 10 um	23.77	27.76	3.98	63.67	1.80	.54
TOTAL	43.87	51.26	7.34	117.54	3.33	

Figure 5-10. Example of CSR data reduction spreadsheet.

SECTION 6

RESULTS AND ANALYSES

TEST CP4

Test and Operating Conditions

Table 6-1 shows the test and operating conditions for each run of test CP4. The first Method 17 runs, with trains A and B, are designated by "M17-A1" and "M17-B1," respectively, where the last digit denotes the run number for that train. The first EGR runs, with trains EGR1 and EGR2, are designated by "CP4-1-1" and "CP4-1-2," respectively, where "CP4" denotes the entire test, the first digit denotes the set or replication number, and the last digit denotes the EGR train.

The stack gas velocity averaged 12.2 m/s (39.9 ft/s) for the entire test, and the run averages varied by -16 to 12%. During runs the velocity varied as much as -23 to 16% from the run mean. The gas temperature averaged 131 °C (267 °F) for the entire test, and the run averages ranged from 113 °C to 149 °C (235 °F to 300 °F). Variation of temperature during runs was relatively high, for example, from 230 °F to 396 °F in the fifth test set. The percent isokinetic for EGR1 and EGR2 trains averaged 103% and 100%, respectively, with extremes of 109% (EGR1) and 93% (EGR2). For the Method 17 trains the corresponding percent isokinetic averaged 99% and 100%, not varying by more than 2% from isokinetic. The cut points of Cyclone I, as calculated by equation 7-6, varied from 10 μm by no more than 0.46 μm (4.6%). In these sets of runs the total particulate mass collected ranged from 400 to 900 mg with the Method 17 trains and 100 to 300 mg with the EGR trains.

Results

Table 6-2 gives the measured particulate concentrations of the CP4 test series including the fraction classified as PM_{10} and comparisons of results in each set of runs. The rightmost column gives the percent error of the EGR trains using the averages of paired Method 17 runs in each set as the reference values. During run CP4-1-2 the filter was ruptured, so the results of this run were excluded from consideration. Table 6-3 gives results of statistical analyses of these data.

Summary of Concentrations and PM_{10} Fraction--

Summaries of the measured particulate concentrations and PM_{10} fractions are given at the bottom of Table 6-2. The PM_{10} fraction averaged 43% with a standard deviation of 3.7%. Particulate concentrations for the >10-um fraction, the <10-μm fraction, and total PM mass averaged 103.2, 77.47, and 206.9 mg/DSCM (0.04508, 0.03385, and 0.09039 gr/DSCF), respectively, with standard deviations of 27, 27, and 25%. The summary values given for total concentration were obtained from the Method 17 results only. Obviously the temporal variation for PM_{10} fraction was much less than the temporal variation of concentration.

TABLE 6-1. RUN PARAMETERS FROM TEST CP4

Test Set ID	Stack Velocity (fps)			Stack Temperature (°F)			Average Sample Flow Rate (acfm)	Isokinetic Ratio (%)	Cyclone Flow Rate (acfm)	Average Recycle (%)	Calculated Cyclone D_{50} (μm)
	Low	Avg	High	Low	Avg	High					
M17-A1		37.6			258		1.122	100.0	--	--	--
M17-B1		37.6			258		1.151	101.9	--	--	--
CP4-1-1	27.4	40.2	41.6	261	287	310	.436	98.4	.634	31.2	10.05
CP4-1-2		40.7			287		.426	93.3	.611	30.2	10.33
M17-A2		41.1			295		1.248	101.7	--	--	--
M17-B2		41.1			295		1.243	100.0	--	--	--
CP4-2-1	31.8	40.4	44.6	218	235	256	.483	108.6	.573	15.7	10.21
CP4-2-2		40.2			235		.485	107.3	.579	16.3	10.13
M17-A3		42.2			244		1.241	98.5	--	--	--
M17-B3		42.8			244		1.266	97.8	--	--	--
CP4-3-1	36.2	45.1	49.4	259	292	340	.544	109.4	.618	12.0	10.28
CP4-3-2		43.4			293		.525	106.9	.622	15.6	10.25
M17-A4		44.0			306		1.303	99.2	--	--	--
M17-B4		44.1			306		1.343	100.7	--	--	--
CP4-4-1	32.6	40.1	44.2	226	244	259	.428	96.9	.583	26.5	10.19
CP4-4-2		39.6			244		.429	96.3	.578	25.9	10.25
M17-A5		43.0			258		1.265	98.6	--	--	--
M17-B5		43.0			258		1.306	100.4	--	--	--
CP4-5-1	36.5	39.8	43.7	230	297	396	.453	103.3	.615	26.4	10.38
CP4-5-2		39.2			297		.441	100.2	.609	27.5	10.46
M17-A6		41.7			281		1.241	99.7	--	--	--
M17-B6		41.7			281		1.247	98.9	--	--	--
CP4-6-1	32.9	38.8	43.9	225	240	255	.435	101.7	.604	27.9	9.89
CP4-6-2		38.3			240		.438	101.7	.594	26.3	10.01
M17-A7		39.9			247		1.178	98.9	--	--	--
M17-B7		40.0			247		1.218	100.7	--	--	--
CP4-7-1	31.2	36.1	41.4	225	248	264	.395	99.3	.583	32.2	10.23
CP4-7-2		36.1			248		.395	97.5	.585	32.4	10.21
M17-A8		38.9			256		1.140	98.2	--	--	--
M17-B8		38.9			257		1.178	100.1	--	--	--

TABLE 6-2. LOADING COMPARISONS BETWEEN EGR1, EGR2, M17A, AND M17B— FROM TEST CP4

Test Set ID	PM_{10} Fraction (%)	Particle Loadings >10μm (gr/dscf)	Particle Loadings <10μm (gr/dscf)	Particle Loadings Total (gr/dscf)	Within Technique Variation (percent difference) <10μm	Within Technique Variation (percent difference) Total mass	Within Technique Variation (percent difference) PM_{10} fraction	Percent Error (EGR from Method 17)
CP4-1								
EGR-1	43.2	.04302	.03276	.07577	--[a]	--[a]		-10.9
EGR-2	38.8	.04100	.02598[a]	.06698[a]				--
M17-A	--	--	--	.07680	--	-19.4		
M17-B	--	--	--	.09330				
CP4-2								
EGR-1	40.8	.04280	.02956	.07237	-6.3	0.7	-3.0	-20.7
EGR-2	43.8	.04038	.03149	.07188				-21.2
M17-A	--	--	--	.09280	--	3.4		
M17-B	--	--	--	.08970				
CP4-3								
EGR-1	45.4	.03811	.03169	.06979	-4.5	-1.8	-1.2	-18.2
EGR-2	46.6	.03796	.03314	.07109				-16.7
M17-A	--	--	--	.08280	--	-6.0		
M17-B	--	--	--	.08790				
CP4-4								
EGR-1	41.6	.03303	.02358	.05662	4.3	6.4	-0.9	-7.9
EGR-2	42.5	.03055	.02258	.05312				-13.6
M17-A	--	--	--	.05920	--	-7.3		
M17-B	--	--	--	.06370				
CP4-5								
EGR-1	45.2	.06279	.05191	.11470	-2.7	-1.6	-0.6	-12.3
EGR-2	45.8	.06321	.05333	.11654				-10.9
M17-A	--	--	--	.12590	--	-7.4		
M17-B	--	--	--	.13560				
CP4-6								
EGR-1	35.0	.06068	.03268	.09335	-7.1	-3.7	-1.2	-10.5
EGR-2	36.2	.06180	.03510	.09690				-7.0
M17-A	--	--	--	.10380	--	-0.9		
M17-B	--	--	--	.10470				
CP4-7								
EGR-1	47.9	.03482	.03197	.06679	2.0	-5.2	3.3	-10.5
EGR-2	44.6	.03901	.03135	.07036				-5.7
M17-A	--	--	--	.07540	--	-2.0		
M17-B	--	--	--	.07390				
Test Average	43.0	.04508	.03385	.09039				
Std. Dev (%)	3.7	27.0	26.6	24.6				

[a] EGR filter ruptured and these results were not used in data reduction.

TABLE 6-3. CP4 STATISTICAL RESULTS

	Paired Runs				
	EGR				EGR-M17
	<10μm	Total mass	PM_{10} fraction	M17 Total mass	Total mass
Average error (%)	-2.4	-0.9	-0.6 (-1.4)[b]	-5.1 (-2.7)[c]	-12.8 (-9.8)[d]
Std deviation (%)	4.6	4.1	2.1 (0.9)[b]	7.7 (4.8)[c]	5.0 (2.7)[d]
95% CI for average (%)[a]	±4.9	±4.3	2.2 (1.2)[b]	±7.1 (±5.1)[c]	±3.0 (±2.2)[d]
95% CI for std. dev. (%)[a]	2.9→11.3	2.6→10.0	1.3→5.1 (0.6→2.7)[b]	5.0→17.0 (3.0→11.9)[c]	3.6→8.3 (1.8→5.4)[d]

[a]95% Confidence interval.

[b]Run Sets CP4-7 eliminated by Dixon (1953) Outlier Analysis.

[c]Run Sets CP4-1 eliminated by Dixon (1953) Outlier Analysis.

[d]Run Sets CP4-4 through CP4-7.

Precision--

The precision (percent difference of paired runs) of the EGR technique varied from -7 to 2% for PM_{10} (<10 μm), from -5 to 6% for total mass, and from -3 to 3.3% in PM_{10} fraction. The corresponding standard deviations of these differences were 4.6, 4.1, and 2.1%, respectively (see Table 6-3 for confidence intervals of the standard deviations). The corresponding averages of the differences, measuring bias between trains, were -2.4, -0.9, and -0.6 with confidence intervals of ±4.9, ±4.3, and ±2.2. None of these small indicated biases were significant at the the 95% confidence level. Note that outlier analysis (Dixon, 1953) indicates that the highest observed difference in PM_{10} fraction (3.3%) is an outlier. If this value is excluded, the observed standard deviation for the PM_{10} fraction is reduced to 0.9%.

The precision of Method 17 varied from -19 to 3% with a standard deviation of 7.7%. Outlier analysis (Dixon, 1953) indicates that the -19.4% value (test set CP4) is not representative. Excluding that value gives a standard deviation of 4.8%. The average percent differences between the Method 17 trains (measuring bias) was -5.1 ±7.1 (or -2.7 ±5.1 excluding the outlier value). Neither of these values for bias is significant at the 95% confidence level.

The observed percent standard deviations with the EGR trains were the same or smaller than that of Method 17. This indicates that the precision of the EGR technique in measurement of both PM_{10} and total particulate emissions is equivalent to the precision of Method 17.

Error of EGR for Total Particulate Matter--

The results with the EGR trains for total mass were consistently lower than the Method 17 results, rightmost column of Table 6-2, ranging from -21 to -6%. The error averaged -12.8 ±3% and exhibited a standard deviation of 5% (given in Table 6-3). Further analyses were performed to identify the source of this error. Since the separation between the EGR probes was increased for the last four sets of runs to reduce obstruction of gas flow by the cyclones, and traversing was eliminated for the last three sets of runs to reduce the effect of the Method 17 probes sampling nearer to the stack wall (see discussion in Section 5), statistics were recalculated for the last four sets of runs. These runs gave an average error of -9.8 ±2.2% with standard deviation of 2.7. Although gas flow disturbance and dust blowing off the wall may have been contributors, these effects were small relative to the total error.

In principle, the error with the EGR train for total concentration could have been due to anisokinetic sampling within the limits for both techniques. Analysis was also performed to estimate this portion of the apparent error. As seen from Eqn. 3-1, the aspiration coefficient of a nozzle is proportional to R (the ratio of stream velocity to nozzle velocity), the inverse of percent isokinetic. Thus, the difference in anisokinetic sampling error between the EGR and Method 17 trains is proportional to the difference between the R values for EGR (R_{EGR}) and Method 17 (R_M).

Linear regression was performed between percent error for EGR (values in Table 6-2) and the difference between EGR and Method 17 values of R ($R_{EGR} - R_M$). This resulted in the equation

$$\text{EGR percent error} = 0.89\ (R_{EGR} - R_M) - 10.6 \qquad (6\text{-}1)$$

with a correlation coefficient of 0.83, accounting for 65% of the variation in EGR error. This analysis indicates that without anisokinetic sampling error, the average error for the EGR probe was still 10.6%.

TEST CP5

Test and Operating Conditions

Table 6-4 shows the test and operating conditions for each run of Test CP5. The first Method 17 runs, with trains A and B, are designated by "M17-A9" and "M17-B9" respectively, where the last digit denotes the run number for that train. This set was obtained prior to runs of the other trains. The first set simultaneous with the CSR and EGR runs was "M17-A10" and "M17-B10". The first EGR run is designated by "CP5-1-EGR". The EGR train used in this test was the same as EGR1 in the preceding test (CP4). The first runs with CSR trains are designated "CP5-1-S1 and "CP5-1-S2," respectively, where the "S1" and "S2" identify the CSR train.

During the first two sets of runs (CP5-1 and CP5-2), the stack gas velocity averaged 11.6 m/s (38 ft/s) with variations during runs of about ±10%. Because of the kiln shutdown, discussed in Section 5, the velocity was lower, averaging 10.3 m/s (34 ft/s) with extremes from -12 to 7%. Variations of velocity during runs was only ±2%. The gas temperature averaged 93 °C (200 °F) for the entire test and the run averages ranged from 113 °C to 149 °C (127 °F to 274 °F). Variation of temperature during runs was less than in the previous test (CP4), 17 °C to 33 °C (30 °F to 60 °F). The percent isokinetic for CSR runs averaged 103%, varying from as low as 81% to as high as 125%. The permissable percent isokinetic for the nozzle sizes used, 0.1 and 0.08 cm, ranged from 67% to 150%. For the EGR runs, the percent isokinetic averaged 101%, not varying from isokinetic by more than 2%. For the Method 17 runs, percent isokinetic averaged 101%, varying from as low as 97% to as high as 105%. The cut points of Cyclone I, as calculated by the equation given in 7-6 varied from 10 μm by no more than 0.3 μm (3%). In these sets of runs, the total particulate mass collected ranged from 400 to 900 mg with th Method 17 trains, 100 to 300 mg with the EGR trains, and 200 to 500 mg with trains.

Results

Table 6-5 gives the measured particulate concentrations of the CP5 test series including the fraction classified as PM_{10} and comparisons of results in each set of runs. The second column from the right gives the percent

TABLE 6-4. RUN PARAMETERS FROM TEST CP5

Test Set ID	Stack Velocity (fps) Low	Avg	High	Stack Temperature (°F) Low	Avg	High	Average Sample Flow Rate (acfm)	Isokinetic Ratio (%)	Cyclone Flow Rate (acfm)	Average Recycle (%)	Calculated Cyclone D_{50} (μm)
M17-A9		35.9			250		1.075	100.3	--	--	--
M17-B9		35.9			250		1.189	109.5	--	--	--
CP5-1-S1	33.9	39.0	39.2	207	258	274	0.601	113.0	0.601	--	10.2
CP5-1-S2		39.1			261		0.621	106.8	0.621	--	9.9
CP5-1-EGR		39.6			242		0.404	100.3	0.606	33.2	9.9
M17-A10		38.0			246		1.121	98.7	--	--	--
M17-B10		38.0			246		1.187	103.3	--	--	--
CP5-2-S1	34.1	36.5	43.8	219	231	268	0.574	115.3	0.574	--	10.3
CP5-2-S1		36.6			232		0.595	107.4	0.585	--	10.1
CP5-2-EGR		36.6			241		0.432	99.1	0.593	27.0	10.1
M17-A11		36.7			231		1.095	100.0	--	--	--
M17-B11		36.7			231		1.140	102.7	--	--	--
CP5-3-S1	32.5	33.7	33.9	205	224	242	0.574	124.7	0.574	--	10.2
CP5-3-S2		33.8			226		0.590	117.3	0.590	--	10.0
CP5-3-EGR		33.1			225		0.372	102.0	0.582	36.1	10.0
M17-A12		32.5			231		0.982	101.2	--	--	--
M17-B12		32.5			231		1.013	103.1	--	--	--
CP5-4-S1	32.0	33.3	33.4	129	131	159	0.496	81.4	0.496	--	10.1
CP5-4-S2		33.4			134		0.506	83.9	0.506	--	9.9
CP5-4-EGR		32.9			136		0.366	101.0	0.501	27.0	10.0
M17-A13		32.5			138		0.959	98.9	--	--	--
M17-B13		32.5			138		0.985	100.2	--	--	--
CP5-5-S1	31.1	32.3	32.5	138	143	185	0.507	85.5	0.507	--	10.1
CP5-5-S2		32.3			146		0.518	88.4	0.518	--	9.9
CP5-5-EGR		31.9			148		0.359	102.0	0.515	30.3	10.0
M17-A14		32.2			154		0.970	100.6	--	--	--
M17-B14		32.3			154		0.996	102.0	--	--	--

(Continued)

TABLE 6-4. (Continued)

Test Set ID	Stack Velocity (fps) Low	Avg	High	Stack Temperature (°F) Low	Avg	High	Average Sample Flow Rate (acfm)	Isokinetic Ratio (%)	Cyclone Flow Rate (acfm)	Average Recycle (%)	Calculated Cyclone D_{50} (μm)
CP5-6-S1	28.9	29.9	30.4	160	177	200	0.531	124.7	0.531	--	10.2
CP5-6-S2		29.1			179		0.542	121.7	0.542	--	10.0
CP5-6-EGR		29.5			179		0.333	100.3	0.524	37.8	10.2
M17-A15		28.6			186		0.880	103.1	--	--	--
M17-B15		28.6			186		0.907	104.9	--	--	--
CP5-7-S1	35.5	35.6	36.1	181	209	245	0.557	107.6	0.557	--	10.1
CP5-7-S2		36.0			212		0.576	107.5	0.576	--	9.9
CP5-7-EGR		35.7			210		0.400	101.5	0.551	27.5	10.2
M17-A16		32.9			204		0.994	101.2	--	--	--
M17-B16		32.9			204		1.032	103.7	--	--	--
CP5-8-S1	35.2	36.2	36.2	195	216	229	0.565	114.4	0.565	--	10.2
CP5-8-S2		36.3			218		0.582	107.8	0.582	--	9.9
CP5-8-EGR		35.8			218		0.402	102.0	0.562	28.5	10.2
M17-A17		34.8			211		1.047	100.8	--	--	--
M17-B17		34.8			211		1.074	102.0	--	--	--
CP5-9-S1	34.4	35.3	35.4	190	203	217	0.561	85.9	0.561	--	10.2
CP5-9-S2		35.3			203		0.567	88.0	0.567	--	10.0
CP5-9-EGR		34.9			205		0.381	102.1	0.544	27.7	10.3
M17-A18		36.1			194		1.041	96.6	--	--	--
M17-B18		36.1			194		1.092	100.0	--	--	--

TABLE 6-5. LOADING COMPARISONS BETWEEN EGR1, CSR-1, CSR-2, M17A, AND M17B— FROM TEST CP5

Test Set ID	PM_{10} Fraction (%)	Paired Runs Particle Loadings >10μm (gr/dscf)	Paired Runs Particle Loadings <10μm (gr/dscf)	Paired Runs Particle Loadings Total (gr/dscf)	Within Technique Variation (percent difference) (<10μm)	Within Technique Variation (percent difference) Total mass	Within Technique Variation (percent difference) PM_{10} fraction	Percent Error (EGR & CSR from M17)	PM_{10} Between Technique Variation (percent difference, CSR-EGR)
M17-A9	--	--	--	0.1305	--	--		--	--
M17-B9	--	--	--	0.1268	--	2.9		--	--
CP5-1-S1	71.5	0.04271	0.10711	0.14983	--	--		0.6	22.1
CP5-2-S2	69.2	0.04978	0.11156	0.16135	-4.1	-7.4	2.3	8.3	26.1
CP5-1-EGR	60.8	0.05533	0.08582	0.14115	--	--		-5.2	--
M17-A10	--	--	--	0.15260	--	--		--	--
M17-B10	--	--	--	0.14530	--	4.9		--	--
CP5-2-S1	62.9	0.04607	0.07798	0.12404	--	--		-3.2	21.1
CP5-2-S2	62.7	0.04610	0.07736	0.12341	0.8	0.5	0.2	-3.7	20.3
CP5-2-EGR	50.1	0.06287	0.06311	0.12598	--	--		-1.7	--
M17-A11	--	--	--	0.12450	--	--		--	--
M17-B11	--	--	--	0.13190	--	-5.8		--	--
CP5-3-S1	69.4	0.01644	0.03723	0.05367	--	--		6.5	0.4
CP5-3-S2	69.8	0.01517	0.03515	0.05032	5.7	6.4	-0.4	-0.1	-5.3
CP5-3-EGR	63.4	0.02143	0.3708	0.05851	--	--		16.1	--
M17-A12	--	--	--	0.05450	--	--		--	--
M17-B12	--	--	--	0.04630	--	16.3		--	--
CP5-4-S1	57.1	0.02248	0.02988	0.05236	--	--		1.7	13.9
CP5-4-S2	54.2	0.02346	0.02772	0.05119	7.5	2.3	2.9	-0.6	6.5
CP5-4-EGR	53.5	0.02258	0.02599	0.04857	--	--		-5.7	--
M17-A13	--	--	--	0.05300	--	--		--	--
M17-B13	--	--	--	0.05000	--	5.8		--	--
CP5-5-S1	54.4	0.02465	0.02935	0.05400	--	--		11.4	30.0
CP5-5-S2	50.4	0.02586	0.02631	0.05216	11.0	3.5	3.9	7.7	19.2
CP5-5-EGR	46.8	0.02466	0.02169	0.04635	--	--		-4.3	--
M17-A14	--	--	--	0.04620	--	--		--	--
M17-B14	--	--	--	0.05070	--	-9.3		--	--

(Continued)

TABLE 6-5. (Continued)

Test Set ID	PM_{10} Fraction (%)	Paired Runs Particle Loadings >10μm (gr/dscf)	Paired Runs Particle Loadings <10μm (gr/dscf)	Paired Runs Particle Loadings Total (gr/dscf)	Within Technique Variation (percent difference) (<10μm)	Within Technique Variation (percent difference) Total mass	Within Technique Variation (percent difference) PM_{10} fraction	Percent Error (EGR & CSR from M17)	PM_{10} Between Technique Variation (percent difference, CSR-EGR)
CP5-6-S1	60.0	0.02522	0.03783	0.06305	--	--		-23.6	7.0
CP5-6-S2	48.4	0.03814	0.03584	0.07398	5.4	-16.0	11.5	-10.3	1.6
CP5-6-EGR	46.2	0.04103	0.03526	0.07630	--	--		-7.5	--
M17-A15	--	--	--	0.08300	--	--		--	--
M17-B15	--	--	--	0.08190	--	1.3		--	--
CP5-7-S1	54.9	0.03173	0.03867	0.07040	--	--		-7.3	5.6
CP5-7-S2	50.4	0.03762	0.03816	0.07578	1.3	-7.4	4.6	-0.2	4.3
CP5-7-EGR	49.8	0.03685	0.03656	0.07341	--	--		-3.3	--
M17-A16	--	--	--	0.07600	--	--		--	--
M17-B16	--	--	--	0.07590	--	0.1		--	--
CP5-8-S1	55.6	0.03303	0.04128	0.07431	--	--		-8.7	34.3
CP5-8-S2	54.3	0.03332	0.03957	0.07290	4.20	1.9	1.2	-10.4	30.2
CP5-8-EGR	44.0	0.03720	0.02920	0.06640	--	--		-18.4	--
M17-A17	--	--	--	0.07920	--	--		--	--
M17-B17	--	--	--	0.08360	--	-5.4		--	--
CP5-9-S1	50.2	0.03770	0.03807	0.07578	--	--		--	--
CP5-9-S2	53.5	0.03898	0.04484	0.08382	--[a]	--[a]		12.4	38.1
CP5-9-EGR	43.5	0.03963	0.03049	0.07013	--	--		-5.9	--
M17-A18	--	--	--	0.07330	--	--		--	--
M17-B18	--	--	--	0.07580	--	-3.4		--	--
(ramping)[b]									
Test av.	55.4	0.05910	0.08716	0.13527					
Std. dev.(%)	8	9	23	9					
(stable)[c]									
Test av.	49.6	0.03191	0.03418	0.06638					
Std. dev.(%)	7	27	15	23					

[a]CSR-1 pump hose was torn and these results were excluded from data reduction.

[b]Reestablishing operation after power outage during sets 1 and 2.

[c]Stable operation in sets 3 through 9, one kiln in sets 4 through 9.

error of the CSR and EGR trains using the averages of paired Method 17 runs in each set as the reference values. During run CP5-9-S1 the hose between the pump and gas meter was torn, so the results of this run were excluded from consideration. Table 6-6 gives results of statistical analyses of these data.

Summary of Concentrations and PM_{10} Fraction--

Summaries of the measured particulate concentrations and PM_{10} fractions are given at the bottom of Table 6-5. Values are given for each of the two operating conditions. In the first two sets of runs, the PM_{10} fraction averaged 55% with a standard deviation of 8%. Particulate concentrations >10 μm, <10 μm, and total averaged 135.3, 199.5, and 309.6 mg/DSCM (0.0591, 0.08716, and 0.13527 gr/DSCF), respectively, with standard deviations of 9, 23, and 9%. In the last seven sets of runs, the PM_{10} fraction averaged 50% with a standard deviation of 7%. Particulate concentrations >10 μm, <10 μm, and total averaged 73.0, 78.0, and 151.9 mg/DSCM (0.03191, 0.03408, and .06638 gr/DSCF), respectively, with standard deviations of 27, 15, and 23%. CSR values for the larger size particles are subject to larger errors associated with anisokinetic sampling than the EGR approach. Therefore, the summary values for PM_{10} fraction and the concentrations >10 μm were obtained from the EGR results only, whereas both CSR and EGR results were used to obtain the values for the concentration <10 μm. The summary values for total concentration were obtained from the Method 17 results only. Obviously the temporal variation for PM_{10} fraction was much less than the temporal variation of concentration.

Precision--

The precision (percent difference between paired runs) of the CSR technique varied from -4 to 11% for PM_{10} (<10 μm) with a standard deviation of 4.6%. Although small, there appears to have been a bias between the two CSR trains, 4 ±3.8%, which is significant at the 95% confidence level. In principle, part of this difference could be a result of different velocity ratios (anisokinetic sampling) for the two trains. However, linear regression between percent difference and difference in velocity ratio, as described above (in test CP4), indicated a bias of 5% with a correlation coefficient of 0.665. The cause of this 4% bias is likely due to the consistently higher size cut for CSR train 1.

To evaluate the relevance of anisokinetic sampling error to CSR measurements of total mass and PM_{10} fraction, precision of these data were analyzed also. The precision varied from -16 to 6% for total mass and from -0.4 to 11.5% in the PM_{10} fraction. The corresponding standard deviations of these differences were 7.5 and 3.8%, respectively. The averages of the differences, measuring bias between trains, were -2 and 3.3% with confidence intervals of ±6.3 and ±3.2. The correlation coefficient for these parameters with differences in velocity ratios for the two trains (0.06 for total mass and 0.04 for PM_{10} fraction) indicated that anisokinetic sampling had no effect in this test on the precision. Note that outlier analysis (Dixon, 1953) indicates that the highest observed difference in the PM_{10} fraction (11.5%) is an outlier. If this value is excluded, the observed

TABLE 6-6. CP5 STATISTICAL RESULTS

	Paired Runs				Error in Total Mass (relative to M17)				
	CSR			M17					
	<10μm	Total mass	PM_{10} fraction	total mass	CSR	EGR	EGR[b]	EGR[c]	PM_{10} CSR-EGR
Average error (%)	4.0	-2.0	3.3 (2.1)[a]	0.8	-1.8	-4.0	(-6.5)	(-4.8)	16.2
Std deviation (%)	4.6	7.5	3.8 (1.2)[a]	7.4	8.6	8.9	(5.1)	(1.9)	13.1
95% CI for average (%)	±3.8	±6.3	±3.2 (±1.7)[a]	±5.3	±4.4	±6.9	(±4.3)	(±1.7)	±6.7
95% CI for std. dev. (%)	3.0→9.4	5.0→15.3	2.5→7.7 (1.2→4.1)[a]	5.1→13.4	6.4→13.0	6.0→17.0	(3.4→10.4)	(1.2→4.1)	9.7→19.9

[a]Run set CP5-6 eliminated by Dixon (1953) Outlier Analysis.

[b]Run set CP5-3 eliminated by Dixon (1953) Outlier Analysis.

[c]Run set CP5-3 and CP5-8 eliminated by Dixon (1953) Outlier Analysis.

standard deviation for PM_{10} fraction is reduced to 1.2%. As for the PM_{10} concentration, the consistently higher size cut for CSR train 1 probably caused the observed bias.

The precision of the Method 17 trains varied from -9 to 16% with standard deviation of 7.4%. The average percent differences between the Method 17 trains was 0.8 ±5.3. This value for bias is not significant at the 95% confidence level.

The observed standard deviations for PM_{10} with the CSR trains were the same as those observed in test CP4 for the EGR train. Likewise, the precision in values of total mass from the CSR trains was the same as for Method 17. It should be noted, however, that in general this would not be expected to occur if widely differing nozzle diameters, within the allowed limits, were used for CSR runs, because of the differences in percent isokinetic which would occur.

Error of EGR and CSR for Total Particulate Matter--

The error for the EGR train in this test (relative to Method 17) ranged from -18 to 16% with a standard deviation of 9%. The average error, -4 ±7%, is consistent with the error observed in test CP4, except that the indicated error is lower and the standard deviation is higher. Outlier analysis indicate that both the lowest value and highest value are outliers. Excluding the high value results in an average error of -6.5% with standard deviation of 5.1%, and excluding both values gives an average and standard deviation of -4.8 and 1.9 respectively. As found in test CP4 this error does not appear to be related to anisokinetic sampling, since its correlation coefficient with the difference from Method 17 velocity ratio was 0.08.

The error in total mass concentration with the CSR trains ranged from -24 to 12% with standard deviation of 8.6%. The average error was -2 ±4%. This error was somewhat related to anisokinetic sampling, as indicated by a correlation coefficient of 0.53. Linear regression of the error with the difference between CSR velocity ratio, R_S, and Method 17 velocity ratio, R_M, gives the relation

$$\text{CSR percent error} = 0.365\ (R_{EGR} - R_M) - 0.004 \qquad (6\text{-}2)$$

accounting for 24% of the variation in sampling error.

Difference between CSR and EGR for PM_{10} --

The observed difference between the CSR and EGR trains for PM_{10} concentration ranged from -5 to 38% with a standard deviation of 13%. The average difference was 16 ±6.7%. Some (5%) of the variation in this difference can be attributed to differences in velocity ratios of the trains. However, linear regression analysis yielded the same 16% average bias. The probable cause of the significant difference between the CSR and EGR trains in this

test was revealed in laboratory measurements (Williamson et al., 1988) subsequent to this field test. The collection efficiency for Cyclone I was found to increase (smaller size cut) as the nozzle inlet diameter and length decreased. Nonrecycle nozzles with geometry and inlet diameters near those used in this test had a small effect upon cyclone performance, reducing the size cut by less than 0.5 μm. The EGR nozzle and recycle rates used in this test caused a decrease of 2 to 3 μm in the size cut. Thus, the cyclone used with the EGR nozzle collected particulate mass with sizes between 7 and 10 μm, which should have passed on to the filter and been classified as PM_{10}. This indicates the need for modification of the nozzles.

SUMMARY OF TESTS CP4 AND CP5

The precision of a technique is the result of two types of variation, between train and within train variances. These are designated s_t^2 and s_b^2, respectively. Precision is then expressed as the standard deviation, s, for the combined variances:

$$s = \sqrt{s_t^2 + s_b^2}. \qquad (6\text{-}3)$$

Table 6-7 gives values of s for the EGR, CSR, and Method 17 techniques calculated from the data given in Tables 6-3 and 6-6. In these tests, the average difference between trains of the same technique estimates $\sqrt{2}\, s_t$, and the standard deviation of differences estimates $\sqrt{2}\, s_b$. The value for Method 17 was calculated by combining the paired runs from both tests with run set CP4-1, an outlier. Precision was good for all of the techniques and parameters studied in these tests, with variations of about 5% or less. As expected, the precision of the EGR technique was found to be better than the CSR technique. This is due to anisokinetic sampling permitted by the CSR technique.

The accuracy of the EGR and CSR techniques for total mass concentration was found to be -10 and -2% respectively. The cause of the apparent bias of the EGR technique is not known but may relate to the geometry of the nozzle. The geometries of the nozzles used in these tests are given in Section 3. The EGR nozzle protruded 2.8 cm (1.1 in.) in front of the cyclone with a 30° outside taper. The CSR nozzles protruded 3.3 cm (1.3 in.) in front of the cyclone with a 20° outside taper.

It appeared that one or both of the techniques tested biased PM_{10} concentrations, as indicated by the 16.2 ±6.7% difference between the EGR and CSR results. Laboratory measurements of collection efficiency versus particle size (Williamson et al., 1988) indicate that the most likely cause was a decrease in the cut diameter of the cyclone by the geometry of the EGR nozzle. Increasing the distance from the EGR nozzle inlet to the cyclone inlet eliminated this shift in the cyclone cut diameter.

TABLE 6-7. PRECISION AND ACCURACY (PERCENT) MEASURED IN TESTS CP4 AND CP5[a]

	Precision[b]			Accuracy, Total mass
	PM_{10}	Total mass	PM_{10} fraction	
EGR	3.7 (2.1→9.5)	3.0 (1.8→8.0)	1.5 (0.9→4.1)	-9.2±3.6
SIM5	4.3 (2.1→8.6)	5.5 (3.5→12.3)	3.6 (1.8→7.1)	-1.8±4.4
Method 17	-	4.7 (3.5→7.7)	-	-

[a]Precision is represented by standard deviation of combined variation between train and within train.

[b]Values in parentheses give 95% confidence interval.

SECTION 7

PROJECT QUALITY ASSURANCE

The general QA plan closely followed that recommended for Method 5 where applicable, in the EPA's QA Handbook (U.S. Environmental Protection Agency, 1977). Notable differences are described in Section 5 and this section. Table 7-1 summarizes QA activities in the laboratory associated with calibrating and checking the equipment and material used. Table 7-2 presents equipment checks performed on site. These activities are discussed in more detail below. Also, nonroutine checks are described which were performed to analyze potential problems in using these candidate methods.

DRY GAS METERS

Prior to these field tests, the dry gas meters were calibrated to determine the gas meter correction factor. One difference between the calibration procedure and that specified by Method 5 is the flow rates at which calibrations were performed. The sample flow rate for these PM_{10} techniques is restricted by the required cyclone flow rate to less than about 0.45 scfm. For the EGR technique, the sample rate can be as low as 25% of that. Therefore, dry gas meters used in the EGR systems were calibrated over a range of 0.1 to 0.6 cfm. For the CSR technique, the dry gas meter receives all of the cyclone flow, so these meters were calibrated between 0.3 and 0.5 cfm.

Three of the dry gas meters used in these tests were new. Complete calibrations of these (EGR1, EGR2, and CSR-2) were performed just before the tests. At the time of calibrations of the EGR1 and EGR2 systems, the wet test meter normally used as the reference was found to have a leak, so an NBS traceable laminar flow element (LFE) (Merriam, 50MJ10-10F) with accuracy of ±0.5% was used as the flow standard. Figures 7-1 and 7-2 illustrate this type calibration. These figures also show calibration of the sample control orifice, which was performed at the same time. Another wet test meter was obtained before calibration of the CSR-2 dry gas meter. This wet test meter was calibrated by the liquid positive displacement method specified for Method 5.

The dry gas meter used in the CSR-1 sampling system had previously been calibrated as indicated in Table 7-1. A pretest, one-point check of the correction factor was performed just prior to the tests to ensure validity of the calibration.

A major purpose of these tests was to compare results from these four sampling systems. Therefore, after the tests all dry gas meters were recalibrated, referencing to the same wet test meter, by the same operator to minimize relative errors between the systems. These results are shown in Table 7-1 as the dry gas meter calibrations performed on 11-6, 11-7, and 11-22.

TABLE 7-1. LABORATORY CALIBRATIONS AND CHECKS OF FIELD EQUIPMENT (Cement Plant Test: 10/2 to 11/1/85)

Equipment	I.D. Number	Calibration Reference	Date	Calibration Parameters	Cal Check Deviation	Allowable Deviation	Comments
Pitot Tube	EGR1	Std Pitot	10-16-85	C_p=0.83	---	---	See text
Sampling Nozzles	EGR1-2	Micrometer	10-19-85	D = 0.1835 in.	--	--	
	EGR1-2	"	10-29-85	D = 0.1835 "	--	--	Repaired and calibrated
	EGR2-2	"	10-19-85	D = 0.1853 "	--	--	
	PC1-7	"	10-19-85	D = 0.2368 "	--	--	
	PC1-8	"	10-19-85	D = 0.2042 "	--	--	
	PC1-8	"	10-29-85	D = 0.2086 "	--	--	Repaired and calibrated
	PC2-7	"	10-19-85	D = 0.2352 "	--	--	
	PC2-8	"	10-19-85	D = 0.2133 "	--	--	
	PC2-8	"	10-29-85	--	0.5%	±2.0%	
PM_{10} samplers (Cyclone I)	EGR1, EGR2, CSR-1, CSR-2	Monodispersed aerosol	1977,1979, 1983	--	--	--	Laboratory calibrations (see text)
Vacuum Gauges	All systems	Hg Manometer	10/85	---	<1.0 in.Hg	±1.0 in.Hg	$P_{act}=K*P_{mtr}$
	EGR1	"	11-5&6-85	K = 1.038	--	--	
	EGR2	"	11-5&6-85	K = 1.038	--	--	Posttest calibrations performed for analysis flow audit procedures.
	CSR-1	"	2-10-86	K = 1.048	--	--	
	CSR-2	"	2-10-86	K = 1.005	--	--	
Laminar Flow Elements	EGR1 Total	External LFE	10-13-85	M=0.2298,B=-0.0058	--	--	Q = M*ΔP+B
	"	LFE & WTM	11-5&6-85	---	2.3%	±5.0%	External LFE
	EGR1 Recycle	External LFE	10-13-85	M=0.0948,B=-0.0007	--	--	(NBS traceable)
	"	"	11-5-85	---	6.3%	±5.0%	WTM - Wet Test Meter
	EGR2 Total	"	10-13-85	M=0.2201,B=0.0075	--	--	Recycle LFE used for on-site flow checks only.
	"	LFE & WTM	11-5&6-85	---	1.5%	±5.0%	
	EGR2 Recycle	External LFE	10-13-85	M=0.0999,B=0.00008	--	--	Laminar Flow
	"	"	11-5-85	---	5.9%	±5.0%	Elements (LFE)

(continued)

TABLE 7-1. (Continued)

Equipment	I.D. Number	Calibration Reference	Date	Calibration Parameters	Cal Check Deviation	Allowable Deviation	Comments
Dry Gas Meters	EGR1	External LFE	10-15-85	γ = 1.0103	---	---	NOTE:
	"	WTM	11- 6-85	γ = 0.9940	---	---	Posttest values
	EGR2	External LFE	10-13-85	γ = 0.9981	---	---	used for data
	"	WTM	11- 7-85	γ = 1.0001	---	---	reduction.
	CSR-1	"	11-16-84	γ = 0.9882	---	---	
	"	"	10-17-85	γ = 1.0017	1.4%	±2.0%	
	"	"	11-22-85	γ = 1.0201	---	---	
	CSR-2	"	10-18-85	γ = 1.0148	---	---	
	"	"	11-22-85	γ = 1.0013	---	---	
Sample Orifices	EGR1 .129A	External LFE	9-23-85	$\Delta H@$ = 10.98	---	---	
	EGR2 .129B	"	9-23-85	$\Delta H@$ = 10.89	---	---	
	CSR-1 .130A	"	7- 5-84	$\Delta H@$ = 5.200	---	---	
	"	"	10-14-85	---	4.3%	±10.0%	
	CSR-2 .130B	"	7- 5-84	$\Delta H@$ = 5.124	---	---	
	"	"	10-14-85	---	3.5%	±10.0%	See text
Magnehelic® Gauges	All systems	H_2O Manometer	10/85	---	<±5.0%	±5.0%	
	EGR1 Total	"	12-3-85	---	2.8%	±5.0%	
	EGR1 Inlet	"	12-3-85	---	2.7%	±5.0%	
	EGR1 Recycle	"	11-7-85	---	11.4%	±5.0%	Meter replaced
	EGR2 Total	"	12-3-85	---	-1.1%	±5.0%	after test series
	EGR2 Inlet	"	12-3-85	---	3.9%	±5.0%	(Recycle LFE used
	EGR2 Recycle	"	12-3-85	---	0.5%	±5.0%	for on-site flow
	CSR-1	"	11-12-85	---	4.6%	±5.0%	checks only).
	CSR-2	"	11-12-85	---	2.3%	±5.0%	
Temperature Readouts	EGR1	Ice bath &	10/85	---	<1.0%	±1.5%	
	EGR2	boiling water	10/85	---	<1.0%	±1.5%	

(continued)

TABLE 7-1. (Continued)

Equipment	I.D. Number	Calibration Reference	Date	Calibration Parameters	Cal Check Deviation	Allowable Deviation	Comments
Fyrite Analyzer	10-5020	Atmospheric O_2 Exhaled CO_2	10-22-85 10-22-85	--- ---	<0.5% <0.5%	±0.5% ±0.5%	Atm O_2 = 20.9% Exhaled CO_2 = 4.0%
Barometer	---	Hg Barometer	10/85	---	<0.1 in. Hg	±0.1 in. Hg	
Analytical Balance	Mettler Hk160	Internal & Control weights	Each set	--- ---	<0.2 mg	±0.2mg	
Recovery Reagent	Acetone #2440 KVSC	---	2-19-86	Mr=0.05mg	0.0003% ±0.003%	±0.001%	Mr = avg residue 20 mL reagent (see text)
Critical Orifice	.043A	WTM	11-25-85	K' = 0.316	---	---	Q=0.05645(K')/T Recalibrated because of difficulty with field flow audits.

TABLE 7-2. SUMMARY OF ON-SITE QA PROCEDURES
(Cement Plant Test)

Q/A Check	Metering Device	Reference	Date	Deviation	Allowable Deviation
Flow Audits					
EGR1 (CP4)	Dry Gas Meter	EGR1 Orifice	10-22-85	-1.6%	±3.0%
	Total LFE	"	"	3.9%	±5.0%
EGR2 (CP4)	Dry Gas Meter	EGR2 Orifice	10-22-85	-1.6%	±3.0%
	Total LFE	"	"	2.6%	±5.0%
EGR1 (CP5)	Dry Gas Meter	EGR1 Orifice	10-28-85	-0.2%	±3.0%
	Total LFE	"	"	1.7%	±5.0%
CSR-1 (CP5)	Dry Gas Meter	CSR-1 Orifice	10-28-85	2.8%	±3.0%
CSR-2 (CP5)	Dry Gas Meter	CSR-2 Orifice	10-28-85	1.0%	±3.0%
Leak Checks					
EGR1	Pitot Tube	Pitot ΔP	Each run	0.0%	±0.0%
All Systems	Sampling Train @ -15 in. Hg	DGM	Each run	<0.02 cfm	0.02 cfm
DGM Comparisons					
M17A	Dry Gas Meter	CSR-1 DGM	10-31-85	1.6%	±2.0%
M17B	Dry Gas Meter	CSR-2 DGM	10-31-85	0.01%	±2.0%

EGR Box #1

EGR FLOW SYSTEM CALIBRATION SHEET

DATE 10-15-85 CALIBRATED BY RSMartin P_{BAR} = 29.50 in. Hg

CALIBRATION LFE I.D. 1.5 CFM

ΔH_o ("H_2O)	$T_{LFE_{cal}}$ (°C)	$T_{LFE_{TOTAL}}$ (°C)	T_{DGM} (°C)	$\Delta P_{LFE_{cal}}$ ("H_2O)	$\Delta P_{LFE_{TOTAL}}$ ("H_2O)	ΔP_{INLET} ("H_2O)	ΔP_{RCL} ("H_2O)	V_{DGM} (ft^3)	TIME, θ (min)
.132	67.5		71	0.40				0.992	11.0
.672	67.5		71	.878				2.332	12.0
1.50	"		72	1.28				2.015	7.0
3.68	"		70	2.0				3.106	7.0
4.9	"		70	2.30				2.025	4.0
7.93	"		70	2.935				1.903	3.0

Figure 7-1. Data form for LFE-based DGM calibration (EGR1 DGM).

CALIBRATION OF ORIFICE/DRY GAS METER
USING 1.5 CFM LAMINAR FLOW ELEMENT

I.D.: EGR1 W/.129A ORI (ORI CAL CHECK)
DATE: OCTOBER 15, 1985
OPERATOR: R.S. MARTIN

ORI DIA.: .13 INS.; APPROACH DIA.(INS.): .5
AMBIENT PRESSURE (IN HG): 29.5

	AMBIENT	LFE	ORI/DGM
TEMPERATURES (F):	67.5	67.5	71
GAS MOLECULAR WEIGHT		28.95	
VISCOSITY (MICROPOISE)		181	

RUN TIME (MIN)	DGM VOL (FT3)	DP LFE (IN WG)	DP SYS LFE (IN WG)	DP ORI (IN WG)	DP SYS ORI/DGM (IN WG)	Q LFE (ACFM)	Q ORI/DGM (ACFM)	ALPHA	DRY GAS METER GAMMA
11	.992	.4	0	.132	.132	.09	.09	.08	1.02
12	2.332	.878	0	.672	.672	.20	.20	.42	1.02
7	2.015	1.28	0	1.5	1.5	.29	.29	.93	1.00
7	3.106	2	0	3.68	3.68	.45	.44	2.27	1.00
4	2.025	2.3	0	4.9	4.9	.51	.51	3.01	1.01
3	1.903	2.935	0	7.93	7.93	.65	.65	4.84	1.02
						0.00	0.00	0.00	0.00
						0.00	0.00	0.00	0.00
						SUMS:	2.18	11.54	6.06

PUT BLANKS WHERE NO DATA ARE ENTERED
NOTE: "DP SYS" IS DELTA P BETWEEN ORIFICE INLET & AMBIENT.
EQUATIONS SET UP FOR POSITIVE PRESSURE SYSTEMS. FOR
NEGATIVE PRESSURE SYSTEMS ENTER "DP SYS" AS A NEGATIVE.

AVG A CAL = .3013289 B = .4776265
BEST A CAL = .2949546 A = .3012312
BEST DH@ = 10.55 R^2 = .9998959

RELATIVE STANDARD ERROR OF
4.00 = FLOW RATE (Q) ESTIMATE (%) = .74
-.55 = LARGEST NEGATIVE ERROR (%) = -1.26
7.95 = LARGEST POSITIVE ERROR (%) = .87

AVERAGE GAMMA OF DRY GAS METER = 1.010348
LARGEST NEGATIVE ERROR (%) = .96
LARGEST POSITIVE ERROR (%) = -1.26

NOTE: THIS CALIBRATION USES THE ASSUMPTIONS:

Q = A * (ALPHA)^B WITH CALIBRATION CONSTANTS A & B,
Q = ACAL * SQRT(ALPHA) WITH CALIBRATION CONSTANT ACAL, AND
Q = 0.959 * SQRT(ALPHA/DH@) WITH CALIBRATION CONSTANT DH@.

WHERE Q = ORIFICE FLOW RATE (ACFM), ALPHA = (DH * T)/(PS * MW),
DH = ORIFICE DELTA P (IN WG), T = GAS TEMPERATURE (R),
MW = MOLECULAR WEIGHT OF GAS,
PS = ABSOLUTE PRESSURE AT ORIFICE INLET (IN HG).

Figure 7-2. LFE-based DGM calibration form (EGR1 DGM).

Field audits were also performed on the dry gas meters including those of Entropy Environmentalists, Inc. These procedures are described in a following subsection.

EGR LAMINAR FLOW ELEMENTS

The equation for flow rate of both the total and recycle LFEs was previously described by Williamson et al. (1984) with the following relationship:

$$Q = a\left(\frac{\Delta P T}{P(SPG)}\right)^b \qquad (7\text{-}1)$$

where a,b = calibration constants
T = absolute LFE temperature
ΔP = LFE pressure drop, inches of water
P = LFE pressure, inches of mercury
SPG = gas specific gravity (1.0 for standard air)

This equation was changed to better describe behavior of the LFEs:

$$Q = M\Delta P(\mu_{STD}/\mu_{LFE}) + B \qquad (7\text{-}2)$$

where μ_{STD} = viscosity of standard air (180.1 micropoise)
μ_{LFE} = viscosity of sample gas (micropoise)
M,B = calibration constants

Given flow rate and pressure drop data for an LFE, as well as gas characteristics, a linear regression may be performed to determine the calibration constants M and B.

Merriam LFEs, (models 50MJ10-10 and 50MJ10-11) were used to monitor the total and recycle gas flow rates respectively, within each of the EGR sampling systems. Because of the restrictions of space in the EGR sampling boxes, straight pipe plumbing for a length of 10 diameters at the inlet to the LFEs, as recommended for use of the manufacturer's calibration, was not possible. Therefore, the LFEs were calibrated within each sampling system by using the LFE flow reference described previously. As an added check, supplementary total LFE data were obtained during the posttest calibration check of the EGR system dry gas meters by using a wet test meter as the calibration standard. Sample calibration forms are shown in Figures 7-3 and 7-4. LFE flow was fitted to a linear function by a least squares fit.

Table 7-3 shows the posttest calibration check of the EGR system LFEs. Actual flow is compared with the flow as predicted by pretest calibration. As is shown, the EGR1 total LFE posttest calibration agreed, on the average, with the pretest values to 2.3%. The EGR1 recycle LFE showed an average difference of 6.3%. However, upon examination of Table 7-3, it can be seen

EGR Box #2

EGR FLOW SYSTEM CALIBRATION SHEET

DATE 10-13-85 CALIBRATED BY RSMartin P_{BAR} = 29.54 in. Hg

CALIBRATION LFE I.D. 1.5 LFE

ΔH_o ("H_2O)	$T_{LFE_{cal}}$ (°F)	$T_{LFE_{TOTAL}}$ (°F)	T_{DGM} (°F)	$\Delta P_{LFE_{cal}}$ ("H_2O)	$\Delta P_{LFE_{TOTAL}}$ ("H_2O)	ΔP_{INLET} ("H_2O)	ΔP_{RCL} ("H_2O)	V_{DGM} (ft^3)	TIME, θ (min)
.162	69	69	69	.42	.42	1.8		0.542	5.50
.92	69	70	69	.99	1.0	5.3		.904	4.00
4.0 ±	69	69	69	2.07	2.0	16.0		1.614	3.50
7.83±	69	73	69	2.88	2.80	24.2		1.584	2.50
	69	71	70	0.43	0.4	1.8	1.0		
	69	71	70	1.038	1.0	4.6	2.35		
	69	72	70	1.43	1.4	6.6	3.2		
	69	73	70	2.038	2.0	9.8	4.48		
	69	74	70	2.48	2.4	12.3	5.48		
	69	75	70	2.84	2.8	14.6	6.35		

Leak Check

@25 "Hg leak rate = .002 ft^3/min

Figure 7-3. LFE-based EGR laminar flow element calibration data form (EGR2).

CALIBRATION OF LAMINAR FLOW METER
USING 1.5 CFM LAMINAR FLOW ELEMENT

LFE I.D.: EGR2 TOTAL LFE
DATE: OCTOBER 13, 1985
OPERATOR: R.S. MARTIN

AMBIENT PRESSURE (IN HG): 29.54

	AMBIENT	CAL LFE
TEMPERATURES (F):	69	69
VISCOSITY OF STANDARD AIR:	180.10	
VISCOSITY AT CAL LFE:	179.87 (MICROPOISE)	

TEMP TOTAL LFE (F)	LFE VISC (MICRO P)	CAL DP LFE (IN WG)	DP SYS CAL LFE (IN WG)	DP LFE (IN WG)	DP SYS LFE (IN WG)	Q CAL LFE (ACFM)	Q LFE (ACFM)	ALPHA
69	180	.42	0	.42	1.8	.10	.10	.42
70	180	.99	0	1	5.3	.22	.22	1.00
69	180	2.07	0	2	16	.46	.45	2.00
73	181	2.88	0	2.8	24.2	.64	.61	2.79
71	180	.43	0	.4	1.8	.10	.10	.40
71	180	1.038	0	1	4.6	.23	.23	1.00
72	181	1.43	0	1.4	6.6	.32	.32	1.40
73	181	2.038	0	2	9.8	.46	.45	1.99
74	181	2.48	0	2.4	12.3	.56	.54	2.39
75	181	2.84	0	2.8	14.6	.64	.62	2.78
	0					0.00	0.00	0.00
	0					0.00	0.00	0.00
					SUMS:	3.63	16.17	

PUT BLANKS WHERE NO DATA ARE ENTERED

NOTE: "DP SYS" IS DELTA P BETWEEN LFE INLET & AMBIENT
EQUATIONS SET UP FOR POSITIVE PRESSURE SYSTEMS. FOR
NEGATIVE PRESSURE SYSTEMS ENTER "DP SYS" AS A NEGATIVE.

SLOPE M = .2201992
INTERCEPT Y = .0074938
R^2 = .9990991
RELATIVE STANDARD ERROR OF
FLOW RATE (Q) ESTIMATE (%) = 2.39
LARGEST NEGATIVE ERROR (%) = -4.65
LARGEST POSITIVE ERROR (%) = 2.83

NOTE: THIS CALIBRATION USES THE ASSUMPTION:

Q = M * (ALPHA) + Y WITH CALIBRATION CONSTANTS M & Y,

WHERE Q = LFE FLOW RATE (ACFM),
ALPHA = DP * VISC(STD)/VISC(LFE),
DP = LFE PRESSURE DROP (IN WG),
VISC(STD) = VISCOSITY OF STANDARD AIR (MICROPOISE),
VISC(LFE) = VISCOSITY OF GAS AT LFE (MICROPPOISE).

Figure 7-4. LFE calibration calculation sheet (EGR2 total LFE).

TABLE 7-3. EGR LFE POSTTEST CALIBRATION CHECKS

	Calibration Standard	Actual Flow Rate (acfm)	Predicted Flow Rate (acfm)	Error (%)
EGR1 total LFE	LFE	.171	.177	3.5
	LFE	.307	.315	2.6
	LFE	.443	.475	7.2
	LFE	.130	.131	0.8
	LFE	.261	.268	2.7
	LFE	.399	.403	1.0
	WTM	.395	.396	0.3
	WTM	.278	.278	0.0
			Average	2.3
EGR1 recycle LFE	LFE	.081	.093	14.8
	LFE	.171	.176	2.9
	LFE	.308	.323	4.9
	LFE	.445	.456	2.5
			Average	6.3
EGR2 total LFE	LFE	.182	.183	0.5
	LFE	.307	.314	2.3
	LFE	.436	.446	2.3
	LFE	.135	.139	3.0
	LFE	.260	.270	3.8
	LFE	.425	.443	4.2
	LFE	.526	.528	0.4
	WTM	.222	.226	1.8
	WTM	.302	.302	0.0
	WTM	.409	.411	0.5
			Average	1.9
EGR2 recycle LFE	LFE	.051	.055	7.8
	LFE	.183	.195	6.6
	LFE	.308	.323	4.9
	LFE	.438	.456	4.1
			Average	5.9

that the first point appears to be an "outlier" probably associated with the very low flow rate for this data point. The EGR2 total LFE averaged 1.9% difference between actual and predicted flow rates whereas the recycle LFE of the same system produced an average difference of 5.9%.

Although the recycle LFEs show an undesirable difference between pretest and posttest calibrations, no further action was taken, because the recycle LFE merely serves as a system check and is not a critical part of an EGR system. The total sampler flow rate is set with the total LFE, whereas the nozzle flow rate and sample volume are set and measured with a sample orifice and dry gas meter as in Methods 5 or 17. Most of observed error for the recycle LFE was found to be attributed to variations in the response of the Magnehelic® gauges.

SAMPLE ORIFICES

Each of the four sampling systems (EGR1, EGR2, CSR-1, and CSR-2) set the target sample flow rate according to a sample orifice located at the outlet of the system dry gas meter. The sample orifice calibration equation for EGR had also been changed from a power curve fit, of the form previously given for the laminar flow elements, to the standard equation used by EPA to describe orifice flow metering characteristics:

$$Q = \frac{0.9615}{\sqrt{\Delta H@}} \left(\frac{\Delta P T}{P M}\right)^{1/2} \qquad (7\text{-}3)$$

where
- Q = measured flow rate at gas meter conditions (acfm)
- ΔP = pressure differential across orifice (inches of water)
- T = absolute temperature at the meter
- P = absolute pressure at the meter (inches of mercury)
- M = molecular weight (28.97 for standard)
- $\Delta H@$ = calibration constant

The orifices on the CSR sampling systems were checked prior to the tests to ensure that previous $\Delta H@$ values were still valid. The orifices on the EGR systems were new and thus were calibrated just prior to these tests. Figure 7-5 shows an example data set for an orifice calibration (EGR2).

PITOT TUBES

To monitor the local velocity at a given sampling point, S-type pitot tubes were attached to the side of the PM_{10} cyclone sampler. Because of the size constraints of the PM_{10} train, 1/4-in. tubing was used for the pitot tubes. Also, separate pitot tubes were not used on each individual sampling train. The difficulty in sampling four to five separate trains from essentially the same traverse point required the elimination of some of the individual pitot tubes. Local velocity was determined by the pitot tube of

ORIFICE CALIBRATION SHEET USING 1.5 CFM
LAMINAR FLOW ELEMENT

I.D.: ORIFICE .129A
DATE: SEPTEMBER 23, 1985
OPERATOR: SJG

ORI DIA.: .13 IN APPROACH DIA. = .50 IN
AMBIENT PRESSURE (IN HG): 29.44

	AMBIENT	LFE	ORI/DGM
TEMPERATURES (F):	69.2	69.2	69.2
GAS MOLECULAR WEIGHT		28.95	
VISCOSITY (MICROPOISE)		181	

DP LFE (IN WG)	DP SYS LFE (IN WG)	DP ORI (IN WG)	DP SYS ORI (IN WG)	Q LFE (ACFM)	Q ORI (ACFM)	ALPHA	REYNOLD NUMBER	CSUBD
.73	0	.5	-1.5	.16	.17	.31	1957	.62
1.02	0	1	-2.36	.23	.23	.62	2723	.62
1.25	0	1.5	-3.1	.28	.28	.94	3330	.61
1.43	0	2	-3.7	.32	.32	1.25	3805	.61
1.6	0	2.5	-4.31	.36	.36	1.57	4254	.61
1.75	0	3	-4.88	.39	.40	1.89	4650	.61
2.01	0	4	-5.95	.45	.46	2.52	5336	.61
2.26	0	5	-6.95	.50	.51	3.16	5997	.61
2.5	0	6	-7.9	.56	.57	3.80	6630	.62
2.68	0	7	-8.8	.60	.61	4.44	7105	.61
2.85	0	8	-9.7	.63	.65	5.09	7554	.61
3.02	0	9	-10.55	.67	.69	5.74	8003	.61
3.2	0	10	-11.4	.71	.73	6.39	8478	.61
				0.00	0.00	0.00	0	0.00
				0.00	0.00	0.00	0	0.00
PUT BLANKS WHERE NO DATA ARE ENTERED				SUMS:	5.98	37.73		

NOTE: "DP SYS" IS DELTA P BETWEEN ORIFICE INLET & AMBIENT.
EQUATIONS SET UP FOR POSITIVE PRESSURE SYSTEMS. FOR
NEGATIVE PRESSURE SYSTEMS ENTER "DP SYS" AS A NEGATIVE.

AVG A CAL = .2895889 B = .4948872
BEST A CAL = .2890775 A = .2906921
BEST DH2 = 10.98 R^2 = .9998053

RELATIVE STANDARD ERROR OF

.79	= FLOW RATE (Q) ESTIMATE (%) =	.65
-.96	= LARGEST NEGATIVE ERROR (%) =	-1.05
2.11	= LARGEST POSITIVE ERROR (%) =	.98

NOTE: THIS CALIBRATION USES THE ASSUMPTIONS:
Q = A * (ALPHA)^B WITH CALIBRATION CONSTANTS A & B,
Q = ACAL * SQRT(ALPHA) WITH CALIBRATION CONSTANT ACAL, AND
Q = 0.959 * SQRT(ALPHA/DH2) WITH CALIBRATION CONSTANT DH2.

WHERE Q = ORIFICE FLOW RATE (ACFM), ALPHA = (DH * T)/(PS * MW),
DP = ORIFICE DELTA P (IN WG), T = GAS TEMPERATURE (R),
MW = MOLECULAR WEIGHT OF GAS,
PS = ABSOLUTE PRESSURE AT ORIFICE INLET (IN HG).

Figure 7-5. Example of sample orifice calibration.

the collocated EGR sampling train. The pitot tubes from the CSR system were omitted from use during sampling as well as calibration. Each Method 17 train of Entropy Environmentalist, Inc. had an S-type pitot which was used to set flow rate.

The pitot tubes associated with the EGR sampling system were calibrated as outlined under EPA Reference Method 5 prior to the field tests. By using SRI's wind tunnel facility (12 in. i.d.), the pitot tubes, attached to the appropriate cyclone samplers, were calibrated at various velocities by comparison of pressure differentials with those of a collocated standard pitot (Cp = 0.99). A spare pitot tube was also calibrated in the described geometry. These data are illustrated in Figure 7-6.

Experience indicated, however, that the calibrated pitot coefficients determined ($\overline{C}_p$ = 0.754) were somewhat lower than expected. Section 4.1.5.1.3 of EPA Reference Method 2 states that if the sampling assembly's cross- sectional area obstructs more than 2 or 3% (depending on sampler construction) of the available flow area, the created blockage will artificially decrease the value of the calibration coefficient. A cross-sectional view of the pitot calibration assembly is shown in Figure 7-7. As can be seen, the pitot/sampler assembly blocks approximately 12% of the available area.

Previous work has produced two models which may be used to predict the effect of this blockage phenomenon (Vollare, 1975). For assemblies with a 2.5 in. cylindrical external sheath and a theoretical blockage greater than 3%, the decrease in the value of the pitot tube coefficient can be estimated as a function of the percent blockage by the following:

$$D = 0.9997\ B - 2.0352 \qquad (7\text{-}4)$$

where D = decrease in pitot tube coefficient (percent), and
B = theoretical blockage (percent).

The other model was designed for 1-in. cylindrical samplers with no external sheaths and a theoretical blockage area greater than 2%. Under these conditions the above function becomes the following:

$$D = 1.0515\ B - 1.4531. \qquad (7\text{-}5)$$

Because the PM_{10} cyclone sampler has a cross-sectional geometry which does not match either of Vollare's models, the correct calibration values were determined for each pitot tube by using both of the above equations. Table 7-4 shows the corrected coefficients for the calibrated pitot tubes. As is shown, the corrected values are more nearly equal to 0.83, which is the normally expected value. Because the PM_{10} sampler does not exactly fit either model description, it was decided to use the average value determined from the two models. For all subsequent sampling, the "A" side of each pitot tube, for both EGR1 and EGR2 sampling systems, was used to measure

Pitot Calibration Run Sheet

Pitot I.D. EGR 1 - Calibrated in Cyc 1-Filter Configuration
Date 10-16-85
Operator RSMantia

$C_{p(STD)}$ = 0.99

$$C_{p(TEST)} = C_{p(STD)} \sqrt{\frac{\Delta P_{STD}}{\Delta P_{TEST}}}$$

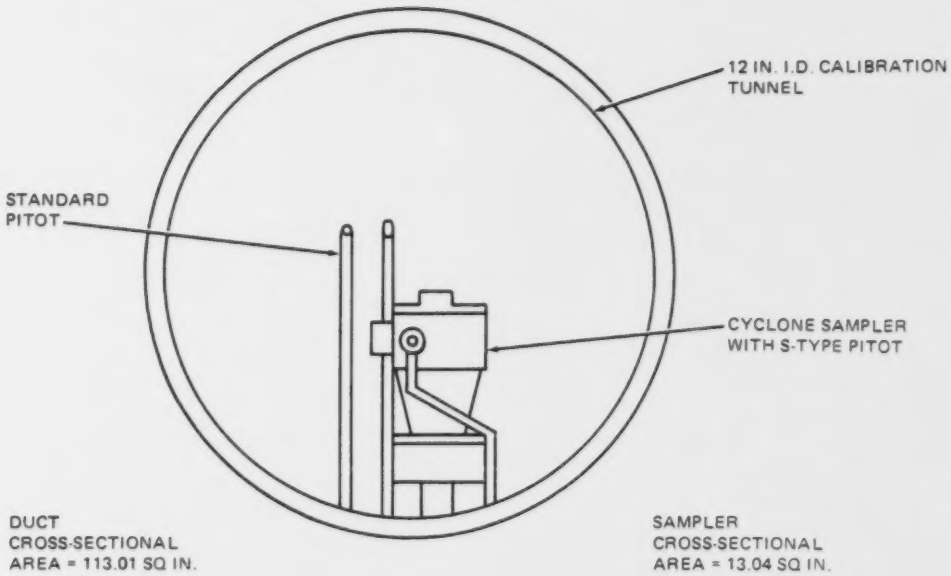
where $C_{p(TEST)}$ = pitot tube coefficient of Type S pitot tube, dimensionless,
$C_{p(STD)}$ = pitot tube coefficient of standard (if unknown use 0.99) type pitot tube, dimensionless,
ΔP_{STD} = standard pitot tube velocity head, inches H_2O, and
ΔP_{TEST} = Type S pitot tube velocity head, inches H_2O.

	ΔP_{STD} (in. H_2O)	ΔP_{TEST} (in. H_2O)	$C_{p(TEST)}$
SIDE A	.072	.122	0.761
	.250	.440	0.746
	.420	.725	0.754
	.572	.958	0.765
	.690	1.22	0.745
SIDE B	.090	.168	0.725
	.200	.378	0.730
	.355	.690	0.710
	.598	1.160	0.711
	.675	1.32	0.708

* Both Sides A & B were leaked checked at 10" H_2O

Average $C_{p(TEST)}$		
	0.754	SIDE A
	0.715	SIDE B

Figure 7-6. Pilot tube calibration form (EGR1).


12 IN. I.D. CALIBRATION TUNNEL
STANDARD PITOT
CYCLONE SAMPLER WITH S-TYPE PITOT
DUCT CROSS-SECTIONAL AREA = 113.01 SQ IN.
SAMPLER CROSS-SECTIONAL AREA = 13.04 SQ IN.

$$\text{CALCULATED BLOCKAGE} = \left(\frac{13.04}{113.01}\right) 100\% = 11.54\%$$

5785-17

Figure 7-7. Pitot calibration geometry.

TABLE 7-4. PITOT CALIBRATION CORRECTIONS

	Calibrated C_p	Corrected C_p Values (2.5-in. model)	(1-in. model)	Average C_p
EGR1				
Side A	0.754	0.833	0.844	0.839
Side B	0.715	0.790	0.806	0.798
EGR2;				
Side A	0.736	0.813	0.820	0.817
Side B	0.730	0.807	0.817	0.812
EGR3 (spare)				
Side A	0.751	0.830	0.841	0.836
Side B	0.767	0.848	0.859	0.854

velocity pressure. On-site comparisons of pitot tube differential pressures between the corrected EGR pitot tubes and those of the Method 17 trains from Entropy Environmentalists, Inc., supported the validity of the above corrections.

MAGNEHELIC® GAUGES

Magnehelic® gauges were used in all of the EGR and CSR sampling systems to monitor pressure differentials related to flow control. The posttest calibration check of Magnehelic® gauges used can be seen in Table 7-5. All Magnehelic® gauges were also checked in this manner before the tests. All of these checks show error less than the limit of ±5% specified by Method 2. The Magnehelic® gauge used to monitor the recycle flow rate of EGR1, however, became suspect during the posttest calibration of that particular LFE. The span was checked (see Table 7-6), and found to be significantly out of specification. Because the recycle LFE serves only as a check, this did not affect test data.

FIELD FLOW AUDITS

SRI field flow audits, as specified in the quality assurance project plan (QAPP), typically have consisted of comparing flow rate measurements of each dry gas meter with the sample flow control orifice of each system. In this test series, a different flow audit system using calibrated critical orifices was added on an experimental basis. During the field tests (CP4 and CP5), a flow audit consisting of a comparison between the flow rate through a critical orifice and the various flow measurement devices within each system was performed. Initial field audit results with the critical orifices were unsatisfactory. The audits indicated all the EGR flow measurement devices from test CP4 apparently exceeded our allowed deviation limits of ±3%. However, comparisons of the sampling orifice with its dry gas meter and total LFE in the manner specified in the QAPP showed acceptable agreement. Likewise, a comparison of the orifices and dry gas meters of both CSR systems showed acceptable agreement, whereas the flow rates measured by these trains did not agree within 5% of the critical orifices. Since each train met the audit requirement of the QAPP, the critical orifice values were disregarded. Figures 7-8 and 7-9 illustrate these flow audit procedures.

Upon completion of the field tests, the critical orifice was recalibrated. The new calibration constant differed from the original by 9% for an unknown reason. When the flow audits previously performed were recalculated with the new constant, the various measurement devices were well within specified limits of the orifice flow rates (see Figure 7-10). The only exception was the EGR1 sampling orifice, which was just outside the 5% error limit for pressure differential or 2.5% limit for flow rate.

To ensure accurate comparability of sample volumes measured by SRI and Entropy personnel, volumes measured by Entropy's Method 17 dry gas meters were compared with the volume measured by SRI's CSR-1 dry gas meter placed

TABLE 7-5. POSTTEST MAGNEHELIC®-CALIBRATION CHECK (in. H_2O) (PERCENT ERROR SHOWN IN PARENTHESES)

A. CSR

Manometer	CSR-1	CSR-2
0.735	0.765 (4.1)	0.74 (0.7)
1.38	1.42 (2.9)	1.40 (1.4)
2.74	2.86 (4.4)	2.85 (4.0)
4.02	4.15 (3.1)	4.15 (3.1)
6.30	6.52 (3.5)	6.42 (1.9)

B. EGR

Manometer	EGR1			EGR2		
	Total	Inlet	Recycle	Total	Inlet	Recycle
0.685	0.663 (3.2)	---	NA[a]	0.690 (-0.7)	---	0.688 (-0.4)
1.44	1.42 (1.4)	---	NA[a]	1.45 (-0.7)	---	1.44 (0.0)
2.52	2.46 (2.4)	---	NA[a]	2.55 (-1.2)	---	2.45 (2.8)
4.15	3.97 (4.3)	4.2 (1.2)	NA[a]	4.22 (-1.7)	4.0 (3.6)	4.17 (-0.5)
8.62	---	8.5 (1.4)	---	---	8.25 (4.3)	---
10.50	---	10.1 (3.8)	---	---	10.0 (4.8)	---
15.88	---	15.2 (4.3)	---	---	15.4 (3.0)	---

[a] EGR1 recycle Magnehelic® calibration check performed separately; instrument was subsequently replaced.

TABLE 7-6. POSTTEST SPAN CHECK OF EGR1 RECYCLE MAGNEHELIC® (in. H_2O)

Manometer Δp	Magnehelic Δp
0.58	0.74
0.80	0.95
1.28	1.36
2.40	2.62
3.18	3.43
4.45	4.85
5.40	5.63

FIELD AUDIT OF GAS FLOW
for
SAMPLING SYSTEMS WITH LEAKLESS PUMPS
and
LEAK CHECK OF PITOT SYSTEM

(Dry Gas Meter Compared to ΔH Orifice)

Sampling Control System ID: MTCS #1 (SIMS-1)

DGM ID: SIMSEP 7E with pretest Y = .9880.

ΔH Orifice ID: C136A with K_{cal} = .5472.

$Q_{DGM} = YQ_{meter}$ (acfm)

$Q_{ori} = \sqrt{\alpha}/K_{cal}$ (acfm)

where $\alpha = T_{DGM}\Delta H/[(P_{bar} + \frac{\Delta H}{13.6})\ 28.97]$

P_{bar} = 29.4 ("Hg)

1. Zero the ΔH gauge.
2. Leak check by plugging the inlet to the sampling system, adjusting the system pressure, P_{sys}, to -15"Hg, and measure the leak rate, .000 (cfm). It must be less than 0.005.
3. Open the inlet to the sampling system and adjust ΔH to 1.55 ("WG). Measure the time to sample 2 ft^3 according to the DGM and record parameters:

DGM	ΔH Orifice	Run Time
Initial: 000.6 (ft^3)	ΔH: 1.55 ("WG)	4.49.72 (min:sec)
final: 002.6 (ft^3)	T_{DGM}: 74 ("R)	(4.83 min)
net = 2.000 (ft^3)		

The run time must fall between 4.56 to 4.84 (min:sec)
The run time range is obtained by:

$t = 2\ Y\ \sqrt{K_{cal}/\alpha}$ = 4.76 min: 0.97t to 1.03t.

LEAK CHECK OF PITOT: ID No. _____ High side is ☐ A or ☐ B

1. Blow gently into high side so that pressure gauge registers 3"-6".
2. Seal the line and observe the gauge for loss of pressure. There should be no detectable leak. Note: With a manometer time is required for the fluid to drain from the walls before a stable reading occurs.

☐ No detectable change for 15 seconds.

Date: 10-24-85 Time of Day: 12:00 Operator: [signature]

Figure 7-8. Orifice/DGM comparison flow audit form (CSR-1).

Field Audit of Flow Measurement Devices
for
Exhaust Gas Recirculation Sampling Systems
and
Leak Check of Pitot System

EGR System I.D. EGR1

DGM ID: EGR1 with pretest γ= 1.010.

ΔH Orifice ID: .1294 with a_o= .2909 and b_o= .4949.

Total Flow LFE: M_T= .2398 and b_T= -.0058.

Recycle Flow LFE: M_R= .0948 and b_R= -.0007.

Critical Orifice ID: NA with K'= NA.

$Q_{DGM}=Q_{METER}\gamma$ (acfm)

$Q_{ori}=a\alpha^b$ (acfm).
where $\alpha=T\Delta H/[P_{BAR}(P_{BAR}+\frac{\Delta H}{13.6})M_d]$

$Q_{LFE}=M(\Delta P\frac{\mu_{STD}}{\mu_{act}})+b$

$Q_{CO}=0.05645K'\sqrt{T_{amb}}$ (acfm)

P_{bar}= 27.65 ("Hg) T_{amb}= 537 (°R)

1. Leak check the negative side of the system by inserting a plug into total flow inlet, shutting off the recycle valve (V_3), and completely opening the sample backpressure valve (V_4). Turn the pump on and adjust the system pressure, P_{sys}, to -19"Hg, and measure the leak rate according to the dry gas meter for one minute.
   Leak rate (negative side): .001 (cfm) --Must be less than 0.005 cfm.
2. Leak check the positive side of the EGR system by closing the sample backpressure valve (V_4), closing the coarse and fine total flow valves, opening the recycle valve (V_3), and connecting the recycle gas outlet to an external leakless pump/dry gas meter assembly. Turn the auxilliary pump on and adjust its system pressure to -19"Hg. Record this leak rate.
   Leak rate (positive side): .004 (cfm) --Must be less than 0.005 cfm.
3. Open the coarse and fine total flow valves and the sample backpressure valve (V_4), and close the recycle valve (V_3). If the audit is performed using a critical orifice proceed using step 4a. If the audit is performed comparing internal flowrates, proceed to step 4b.

4a. Critical orifice--attach critical orifice to the total flow inlet, turn the pump on and adjust the system pressure to -19.0"Hg.

4b. Internal Comparisons--with an "open end" quick connect in the total flow inlet, turn the pump on and set the ~~total flow LFE~~ to a ΔP of ~~NA~~ 2.98 "H_2O.

5. Measure the time to sample 2.000 ft^3 according to the DGM and recording the following parameters:

DGM	ΔH orifice	Total LFE
initial: 57.90 (ft^3)	ΔH= 2.98 ("H_2O)	ΔP_{TOT}= 1.85 ("H_2O)
final: 59.90 (ft^3)	T_{DGM}= 548 (°R)	ΔP_{INL}= 5.7 ("H_2O)
(net 2.000)		T_{TOT}= 549 (°R)

Run time: 4.89 (min)

The run time must fall between 4.81 and 5.11 minutes. ✓
ΔH must fall between NA and NA "H_2O.
ΔP_{TOT} must fall between 1.69 and 1.87 "H_2O. ✓
ΔP_{INL} values have been empirically determined for several individual critical orifices; the recorded value should match the appropriate values below:

CO .059A	ΔP_{INL} = 5.7 "H_2O	CO .059B	ΔP_{INL} = 5.2
CO .043A	ΔP_{INL} = 2.7 "H_2O	CO .043B	ΔP_{INL} = 2.6
CO .031A	ΔP_{INL} = 1.0 "H_2O	CO .031B	ΔP_{INL} = 1.0

10-22-85
RS Martin

Figure 7-9. Flow audit form for critical orifice or internal comparison for the EGR system (EGR1).

FIELD AUDIT OF GAS FLOW
for
SAMPLING SYSTEMS WITH LEAKLESS PUMPS
and
LEAK CHECK OF PITOT SYSTEM

(Dry Gas Meter and ΔH Orifice Compared to a Critical Orifice)

Sampling Control System ID: MTCS #1 (SIHS-1).

DGM ID: SINGER 7E with pretest Y = 0.9880.

ΔH Orifice ID: 0130A with K_{cal} = 5.472.

$Q_{DGM} = Y Q_{meter}$ (acfm)

$Q_{ori} = \sqrt{a/K_{cal}}$ (acfm)

where $a = T_{DGM} \Delta H / [(P_{bar} + \frac{\Delta H}{13.6}) 28.97]$

Critical Orifice ID: 0.043A with K' = 0.3160.

$Q_{co} = 0.05645 K' \sqrt{T_{amb}}$ (acfm)

P_{bar} = 29.4 ("Hg) T_{amb} = 527 (°R)

1. Attach critical orifice to the sampling system inlet and zero the ΔH gauge.
2. Leak check by plugging the inlet to the critical orifice, adjusting the system pressure, P_{sys}, to -19"Hg, and measure the leak rate, _____ (cfm). It must be less than 0.005.
3. Open the inlet to the critical orifice and readjust P_{sys} to -19.0"Hg. Measure the time to sample 2 ft^3 according to the DGM and record parameters:

DGM	ΔH Orifice	Run Time
initial: 101.6 (ft^3)	ΔH: 1.55 ("WG)	4.49.72 (min:sec)
final: 103.1 (ft^3)	T_{DGM}: 74 (°R)	(4.83 min)
net = 2.000 (ft^3)		

The run time must fall between 4:41.4 to 4:58.8 (min:sec)
ΔH must fall between 1.40 to 1.55 " WG.
The ΔH and run time ranges are obtained by:

$\Delta H = 6.80 P_{bar} [\sqrt{1+0.02715 K_{cal} K'^2 T_{DGM}/T_{amb}} - 1]$ = 1.48 ("WG): 0.95ΔH to 1.05 ΔH.

$t = 35.4 Y (\sqrt{T_{amb}}/K' T_{DGM}) (P_{bar} + \frac{\Delta H}{13.6})/P_{bar}$ = 4.84 min: 0.97t to 1.03t.

LEAK CHECK OF PITOT: ID No. _____ High side is ☐ A or ☐ B

1. Blow gently into high side so that pressure gauge registers 3"-6".
2. Seal the line and observe the gauge for loss of pressure. There should be no detectable leak. Note: With a manometer time is required for the fluid to drain from the walls before a stable reading occurs.

☐ No detectable change for 15 seconds.

Date: 10-28-85 Time of Day: 1200 Operator: [signature]

7-23

Figure 7-10. Critical orifice flow audit form for CSR sampling trains (CSR-1).

in series with each of Entropy's gas meters. This, in effect, compared the calibration source of the two contractors. The comparison showed the CSR-1 gas meter agreed with Entropy's M17A gas meter to -1.6% and with Entropy's M17B gas meter to 0.01%.

OTHER TRAIN COMPONENTS

Prior to the field tests the digital temperature readouts of the two EGR systems were calibrated against an ice bath (32 °F) and a boiling water bath (212 °F). Since the readouts produced the appropriate readings (±2 °F), no further checks were performed.

Table 7-7 gives the results of posttest checks of vacuum gauges used during this test series. The agreement with a mercury manometer was within allowable limits of ±10%. This accuracy limit is needed when using a critical orifice for flow audits; the system vacuum is set at 19 ± 2 in. Hg to establish the reference flow within ±2%.

The nozzles used for sampling with the PM_{10} cyclones for both the EGR and CSR systems were calibrated immediately prior to the test program. A micrometer was used to measure the inside diameter of the nozzles to the nearest 0.001 in. The micrometer used for this set of measurements allowed for an estimation to the fourth decimal place. Measurements were made on three separate diameters. The criteria imposed dictated that if the deviation between any two diameters was greater than 0.004 in. the nozzle must be repaired and recalibrated. All the sample nozzles passed this pretest criterion. The average of the three diameters was then defined as the overall nozzle diameter. An example of these measurements (CSR-1 nozzle set FC1) can be seen in Figure 7-11.

Before each sampling run, the nozzles were visually inspected to determine if the nozzles had sustained any damage in the preceding run. In two instances, CSR standard cyclone nozzle FC1-8 and emission gas recycle nozzle EGR1-2, it was necessary to repair and recalibrate a nozzle.

PM_{10} SIZING DEVICE (CYCLONE I)

Advancement of methods for characterizing cyclone behavior has resulted in a new equation for SRI/EPA Cyclone I, used as the single-stage, 10-μm size classifier in previous tests.

The 50% cut diameter (in micronmeters) is given by

$$D_{50} = 0.15625 \left(\frac{M_w P}{T} \right)^{-0.2091} Q^{-0.7091} \mu^{0.7091} \qquad (7\text{-}6)$$

The flow rate for a 10 μm size cut is determined from

$$Q = 2.84 \times 10^{-3} \left(\frac{M_w P}{T} \right)^{-0.2949} \mu \qquad (7\text{-}7)$$

TABLE 7-7. SYSTEM VACUUM GAUGE CALIBRATION CHECKS

		Vacuum Gauge (in. Hg)	Mercury Manometer (in. Hg)	Percent Difference	Average Percent Difference
CSR-1	(11-4-85)	19.0	20.3	6.4	---
CSR-1	(11-5-85)	18.4	19.0	3.2	4.80
CSR-2	(11-4-85)	19.0	19.4	2.1	---
CSR-2	(11-5-85)	19.2	19.0	-1.1	0.50
EGR1	(2-10-86)	19.0	20.1	5.5	---
EGR1	(2-10-86)	18.6	19.0	2.1	3.80
EGR2	(2-11-86)	19.0	19.75	3.8	---
EGR2	(2-11-86)	18.3	19.0	3.7	3.75

Date/Time	Calibrated By	Nozzle ID Number	Nozzle Diameter (inches)			ΔD	D_{avg}
			D_1	D_2	D_3		
10-18-85	RS Martin	FC1-1	.4695	.4685	.4685	.0010	.4688
"	"	FC1-2	.4330	.4330	.4323	.0007	.4328
"	"	FC1-3	.3960	.3952	.3965	.0013	.3959
"	"	FC1-4	.3512	.3500	.3530	.0030	.3514
"	"	FC1-5	.3153	.3157	.3155	.0004	.3155
"	"	FC1-6	.2758	.2730	.2760	.0030	.2749
"	"	FC1-7	.2365	.2372	.2368	.0007	.2368
"	"	FC1-8	.2023	.2050	.2054	.0031	.2042
"	"	FC1-9	.1938	.1922	.1938	.0016	.1933
"	"	FC1-10	.1750	.1738	.1747	.0012	.1745
where:	RS Martin	FC1-8	.2095	.2073	.2090	.0022	.2086

FC1-8 damaged on 10-28-85 during Test run CP5-1-1, repaired and recalibrated

$D_{1,2,3}$ = three different nozzle diameters at 60 degrees to each other. Each measured to the nearest 0.001 inch

ΔD = maximum difference between any two diameters, $\Delta D \leq 0.004$ inch

D_{avg} = $(D_1 + D_2 + D_3) \div 3$

Instructions

1. Inspect the nozzle for nicks, dents, and corrosion. If these are found they should be corrected before calibration.
2. Place a reference mark on the nozzle. Place the nozzle at the center of Figure 1, aligned with Point 1. Measure and record D_1.
3. Rotate the nozzle so that the reference mark is aligned with Point 2. Measure and record D_2.
4. Rotate the nozzle so that the reference mark is aligned with Point 3. Measure and record D_3.
5. Calculate ΔD and D_{avg}.

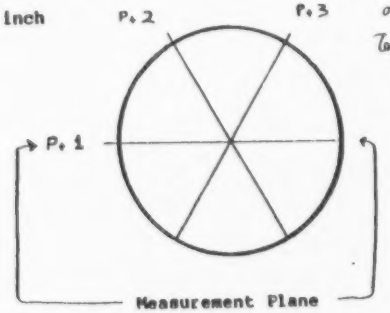


Figure 1

Figure 7-11. Nozzle calibration form (CSR-1 nozzle set FC1).

where Q = flow through the cyclone (acfm)
μ = gas viscosity (micropoise)
T = cyclone gas temperature (°R)
M_w = wet molecular weight of gas
P = absolute stack pressure (inches of mercury)

A series of laboratory tests using Cyclone I were performed to find the empirical equation for determining the 50% cut point of the device. The basis for this equation has been described by Farthing and Williamson (1985) and Williamson et al. (1988).

A commercially available version of the SRI/EPA Cyclone I particle sampler was used as the PM_{10} sizing device for both sets of EGR and CSR sampling systems. The cyclones (Flow Sensor-type) were purchased directly from the current vendor, Andersen Samplers, Inc. Although the outside dimensions of this cyclone differed from the PM_{10} cyclones used for past tests, the inner dimensions were intended to be the same.

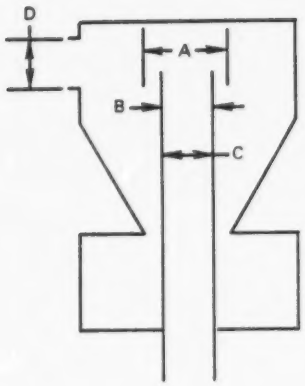
In addition to differences described in Section 3 between the outside dimensions of the SRI/EPA version and the commercial version of this cyclone, a difference in the inner dimensions is shown in Figure 7-12. Dimensions are shown for cyclones machined from the SRI/EPA design drawings (used for the previous EGR and CSR tests) and for the commercial version of Cyclone I used in this test. It can be seen that the turnaround portion (parameter A) of the commercial cyclone has been bored out smaller than the original SRI design. After a search through past drawing files, the current vendor, Andersen Samplers, Inc., determined that the bore specification was incorrectly transposed from 0.59 in. on the original SRI drawings to 0.53 in. on the commercial drawings in August 1981. Particulate matter collected in the turnaround region and outlet tube can be expected to be sensitive to this dimension because the sample gas must pass through the annulus between the turnaround and the exit tube (parameter B).

WATER CONTENT MEASUREMENT

Because the sampling times were relatively short and the test effluent contained only ambient levels of moisture (refer to Section 4), cooled impingers were not used; water content was determined by using drying columns (50 gm capacity). The desiccant used for all test runs was 6-16 mesh indicating silica gel. The stack gas moisture was determined by weighing the drying column before and after each test run with a triple-beam balance. The pre- and postrun drying column weights, along with the net weight gain, were recorded directly on the individual run sheets. Moisture collected ranged from 15 to 25 g for CSR runs.

ELECTRONIC BALANCE

A Mettler HK160 analytical balance was used for determination of pretest and posttest weights. Immediately prior to each weighing session the balance was calibrated according to the manufacturer's instructions by using



	A (INCHES)	A-B (INCHES)	B (INCHES)	C (INCHES)	D (INCHES)
SRI/EPA CYCLONE I					
EGR	0.590	0.100	0.490	0.398	0.500
CSR	0.590	0.097	0.493	0.397	0.500
COMMERCIAL CYCLONE I'S					
EGR1	0.5283	0.0366	0.4917	0.4005	0.5007
EGR2	0.5310	0.0413	0.4897	0.3897	0.5005
CSR-1	0.5283	0.0388	0.4895	0.3802	0.4980
CSR-2	0.5286	0.0377	0.4909	0.3842	0.4967

5785-9

Figure 7-12. Cyclone I dimensions.

an internal 100-g calibration weight. As the weighing progressed, a known control weight was checked to chart any possible calibration drift of the balance. In addition, the balance's electronic zero drift was tracked by allowing the balance to stabilize after each weight (including control weights), and the displayed zero offset was recorded. The actual weight of each sample was determined as the difference of the balance weight and the zero offset recorded after the substrate had been removed from the weighing pan.

MASS (RINSE) BLANKS

During sample recovery, the inside surface of each sampler was rinsed with reagent-grade acetone to remove any particulate matter which remained after the initial brushing. To ensure the acetone itself did not contribute unaccounted mass to the sample, a set of blank rinses was prepared. Approximately the same volume of acetone as used during normal rinse procedures (20 mL or 15.7 g) was placed in an individual, preweighed weighing dish, and the reagent was allowed to evaporate. The blank sample was reweighed to determine the amount of residue left in the dish. As can be seen in Table 7-8, the amount of residue varied from 0.4 mg to -0.2 mg, with an average value of 0.05 mg. It can be shown that when comparing these mass values to the particulate mass sampled (≈100 mg or more), the residue would not be significant. Therefore, for purposes of data reduction, the mass of acetone residue for each run was ignored.

WATER UPTAKE TESTS

To quantify the effects of sample exposure to atmospheric moisture while recovering the sample and during the weighing process, water uptake tests were performed on dust samples extracted from the hoppers of the gravel bed filter. Samples ranging from 498.15 mg to 1406.85 mg were placed in aluminum pans, weighed, and then exposed to the laboratory environment for 5, 10, or 15 min. At the end of the exposure period, the samples were reweighed.

This test was performed for a total of six samples (two samples per exposure period) on two separate dates, October 22 and October 25. The results of these tests are shown in Table 7-9.

A comparison of the values in the table to the mass loadings expected indicates that the weight gain experienced for even a 15-min exposure period would not be significant. As actual cyclone samples would never be exposed to the atmosphere for more than 5 min during weighing, it was considered unnecessary to make any correction for water uptake or make special arrangement to prevent exposure to atmospheric moisture during weighing of the samples.

TABLE 7-8. ACET

ONE RINSE BLANKS

Pan I.D.	Preweight (mg)	Final Weight (mg)	Residue (mg)
A	1502.0	1502.0	0.3
B	1515.6	1515.4	-0.2
C	1518.0	1517.7	-0.3
D	1504.4	1504.8	0.4

TABLE 7-9. WATER U

TAKE OF ASH SAMPLES

Date	5 min exposure	10 min exposure	15 min exposure
10-22-85	0.2	0.1	0.4
	0.2	0.1	0.2
10-25-85	0.0	0.0	0.2
	0.1	0.2	0.2
Average	0.13	0.10	0.25

TABLE 7-10. FILTER WEIGHT CHANGES BETWEEN FIRST AND SECOND WEIGHINGS

		Weight Gains	Weight Losses
Relative to filter mass loading	Number of Filters	9	13
	Average, %	1.25	1.77
	Standard Deviation, %	0.69	0.74
Relative to total PM_{10} Loading	Average, %	0.99	1.18
	Standard Deviation, %	0.38	0.46

MASS LOADING DETERMINATIONS

To determine the dry weight of the collected mass for each run, replicate weighings were performed on each catch (i.e., cyclone, cyclone wash, filter, and filter wash) with at least 8 h of desiccation between weighings. Consecutive weighings which agreed to within ±0.5 mg were considered as sufficient evidence of stable, dry weights. Such weights were obtained after two posttest weighing sessions on all cyclone, cyclone wash, and filter wash catches. The latter wash included washing of the cyclone turnaround cap and exit tube.

Several of the filters displayed weight changes in excess of the above criterion between the first and second weighings. Table 7-10 shows the number of filters affected, the average weight change encountered in percent, and the standard deviation, also in percent. These values are given in terms of both the filter mass loading and the PM_{10} mass loading (filter, filter wash).

Additional weighings were performed on all filters, including those not affected by the above weight changes. Those filters previously demonstrating weight gains showed a continuation of this trend through the third and fourth weighings. Those filters previously showing weight losses approached a stable weight during the additional weighing sessions. Those filters previously showing no weight changes continued to show no change.

The weight gains exhibited were considered to be the result of some anomalous interaction between the filter catch and the surrounding environment. Although the magnitude of the weight gains was small (0.99% of the PM_{10} mass loading on the average), it was decided that the first posttest weight was the most representative of the true sample weight and all subsequent weights should be ignored. Therefore, the first posttest weight was used to determine the mass loading on the filter. For the sake of consistency, the first posttest weight was also used to determine the filter loading for those filters showing weight losses and those not affected by the weight changes.

GAS COMPOSITION ANALYZER

A Bacharach Fyrite gas analyzer set was used to determine the oxygen and carbon dioxide composition of the sample gas. Prior to use, both reagent cylinders were checked, following manufacturer's instruction, to determine the strength of each reagent. The O_2 cylinder was checked with ambient air (20.9% oxygen) and found to provide the correct value. The CO_2 cylinder was compared against exhaled human breath (approximately 4% carbon dioxide).

Each cylinder was used for three successive gas composition determinations. Stack gas oxygen concentrations equal to 21% were found for each of the three runs. Stack gas carbon dioxide concentrations were 0.0%, 0.4%, and 0.5%, producing an average concentration of 0.3% carbon dioxide. These

values are close to those of standard atmospheric air, 20.95% O_2 and 0.03% CO_2 (Weast 1974), verifying that the stack gas was essentially ambient air as expected.

BAROMETRIC PRESSURE

A portable anaeroid altimeter/barometer was used to monitor the local barometric pressure. The portable barometer was compared for calibration against an NBS traceable mercury barometer.

SYSTEM LEAK CHECKS

Each sampling system was leak-checked immediately before and after each test run. The nozzle on the end of the sampling system was plugged, and the system's pump was turned on and adjusted so that the vacuum gauge read 15 in. of mercury. The coarse and fine recycle valves on the EGR systems had to be closed for this test. The dry gas meter was then monitored to determine if a leak rate in excess of 0.02 cfm was present. If an unacceptable leak was found, the system was checked until the leak was found and repaired. After repair, the leak check procedure was repeated until an acceptable result was obtained. The results of each check was recorded directly on the appropriate run data sheet.

The unique plumbing of the EGR systems required that a second leak check also be performed. This was needed to ensure that the recycle (positive) side of the system was also free of leaks. For this test, the coarse and fine total flow valves, along with the sample back pressure valve, were closed. The two recycle valves were turned to the full open position. The recycle output line (using latex or similar tubing) was connected to an external pump/dry gas meter combination (or spare sampling system). A leak check procedure similar to that used for Method 5 was performed, and results were recorded on the appropriate data sheet.

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